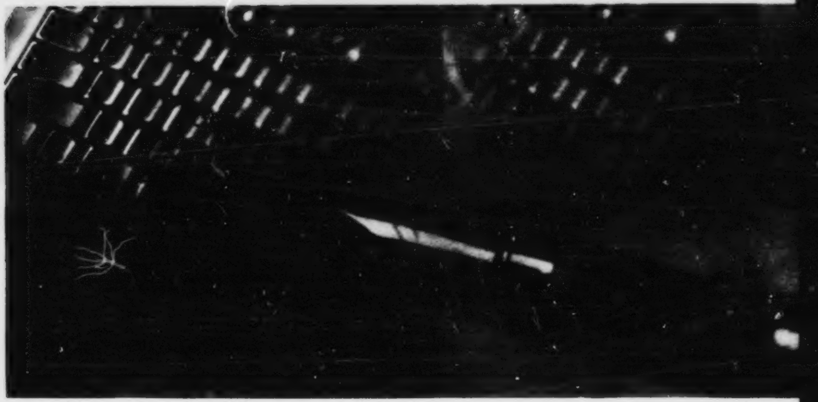
RESEARCH REPORT

THE RENOVATION OF AN APARTMENT BUILDING WITH SOLID MASONRY WALLS



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101-02159/

THE RENOVATION OF AN APARTMENT BUILDING WITH SOLID MASONRY WALLS

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October 1999

The Canada Mortgage and Housing Corporation, the Federal Government's housing agency, is responsible for administering the National Housing Act.

This legislation is designed to aid in the improvement of housing and living conditions in Canada. As a result, the Corporation has interests in all aspects of housing and urban growth and development.

Under Part IX of this Act, the Government of Canada provides funds to CMHC to conduct research into the social, economic and technical aspects of housing and related fields, and to undertake the publishing and distribution of the results of this research.

CMHC therefore has a statutory responsibility to make available information which may be useful in the improvement of housing and living conditions.

This publication is one of the many items of information published by CMHC with the assistance of federal funds.

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DISCLAIMER

This study was conducted by the Saskatchewan Research Council for Canada Mortgage and Housing Corporation under Part IX of the National Housing Act. The analysis, interpretation and recommendations are those of the consultants and do not necessarily reflect the views of Canada Mortgage and Housing Corporation or those divisions of the Corporation that assisted in the study and its publication.

ACKNOWLEDGMENTS

The authors would like to acknowledge the funding of CMHC for this project. Thanks are also extended to the CMHC staff, particularly Duncan Hill and Jim Moorhead.

The owners of the building, particularly Rick Strauss, offered good cooperation during the many tasks of installing, calibrating and checking instrumentation, and thanks are extended to them.

Alison Rolph and Jim Zenner of Prince Albert provided the on-site meter readings and photographs of the wetting patterns. Don Munch, custodian of the building, provided valuable assistance during the many tasks involved. John Conway provided valuable help with the data processing and graphing. SRC staff including Ken Babich, Kim Young, Bob MacPherson, and Brett Smith assisted with the installation of the instrumentation. Mark Bomberg provided much of the experimental design and instrumentation selection. Our thanks are extended to all these for their valuable assistance.

ABSTRACT

A 90-year old building with solid clay brick walls has been gutted and renovated into a multi-family residential building for low income persons. The renovation involved the addition of thermal insulation to the inside of the building envelope, the application of stucco to the exterior of three of the four sides of the building, restoration of the front masonry facade, installation of a mechanical ventilation system with ventilation of each room, and a combination hydronic baseboard/radiant floor heating system. This renovation was of particular interest as it represented a unique opportunity to evaluate the impact of insulating formerly un-insulated solid masonry walls–a subject of much interest and controversy within the building rehabilitation industry. The project also demonstrated how the most current understanding of building envelope durability, heating and ventilation systems and indoor air quality could be implemented within an otherwise unremarkable renovation project.

The building envelope was monitored for thermal and moisture performance. Energy, water use and indoor air quality were also monitored in the renovated building.

Based on 15 months of measured readings of wood moisture pins placed in the walls and attic of the retrofitted building, the rehabilitation has been successful in reducing wall heat flow by conduction while maintaining safe moisture content levels in the wood members. The indoor air quality in the building was greatly improved through the use of a mechanical ventilation system with ventilation provided to each room in each apartment.

EXECUTIVE SUMMARY

The Building Performance Section (BPS) of the Saskatchewan Research Council (SRC) was contracted by the Canada Mortgage and Housing Corporation to conduct a research project titled "A Case Study of the Renovation of an Apartment Building With Solid Masonry Walls". The building studied was a four-storey masonry building with 30 suites located in Prince Albert, Saskatchewan, Canada that was originally built about 1910, and renovated in 1996 and 1997. Funds were made available from the RRAP Program of Canada Mortgage and Housing Corporation to assist with the renovation of the building in order to increase the supply of upgraded low-income housing.

The SRC project team worked closely with the building owners, CMHC representatives, the local project manager, the design team, and the contractors to advise on and document the renovation of the building.

During the course of renovation, the building was completely stripped to the exterior walls and roof including the removal of the concrete basement floor. Numerous instruments and sensors were installed throughout the building envelope to provide continuous measurements of temperature, relative humidity, air pressure differentials, and indoor environment. Two types of rain penetration sensors were installed in the exterior walls at six locations in the exterior walls. Wood moisture contents were monitored in the attic floor joists. Heat flux transducers were used to measure the heat flow through the walls. A weather station was located on the roof of the building to provide outside weather conditions including wind speed and direction, rainfall, temperature, relative humidity and solar radiation levels. All of the instrumentation was connected to a multi-channel data logger located in the building, which accumulated data continuously at half-hour intervals over the 15 month monitoring period. Approximately 52 megabytes of data was collected by the data logging system over the monitoring period, which extended from August 1997 to November 1998. This data will be used for cross-checking computer models of moisture and heat transfer in walls and to assess the potential durability of the walls. A local Prince Albert contractor was retained to photograph rainfall patterns on the exterior building envelope and also to record energy and water meter readings.

The HOT-2000 energy analysis software was used to model the building's energy use. The model had to be customized to handle the size of the building. Energy use was metered using the utility supplied electricity, natural gas, and water meters, along with 4 additional natural gas meters used to measured the consumption of the three natural gas boilers and one natural gas water heater.

The renovation of the building included insulation added to the inside of the walls and roof, new windows and doors, new polyethylene air- and-vapour barrier, new gypsum board, new flooring, a ventilation system, a new radiant floor heating system, and a new roof membrane. Three sides of the exterior of the building had new stucco applied. The front side of the building did not have stucco applied, as the building front facade was of heritage interest in an older part of Prince Albert.

A blower door test was used in connection with pressure taps located part way through the walls to determine the tightness of various elements in the wall system.

The continuous data collection showed a high level of integrity over the 15-month monitoring period, with excellent reliability of the sensors and immunity of the system to electrical disturbances. A modem was installed to allow remote checking of the monitoring data and to provide for downloading of the data from the site to SRC's office in Saskatoon, approximately 150 km away. This modem installation greatly improved the quality of the data collected.

Some of the key findings from the study include the following:

1. The addition of stucco to the masonry walls has reduced the likelihood of water movement into the masonry wall, based on the moisture readings from the wall locations. The locations with the stucco on the exterior experienced much smaller rises in moisture content due to rain than did the location where no stucco was present on the brick.

2. Based on a comparison of pressure drops through the brick wall and the stud wall, the bulk of the air tightness layer in the exterior wall is provided by the brick wall. There is a layer of stucco on the outside of the brick on three sides of the building, and a layer of parging on the inside of all four walls. An interior wood stud wall with a sealed polyethylene vapour barrier was used. The overall air tightness of the building was 2.04 cm^2/m^2. For comparison, the R-2000 standard is 0.7 cm^2/m^2.

3. The new mechanical ventilation system was able to maintain good indoor air quality in the suites and common areas. The ventilation system was designed so that each room in each suite was provided with an exhaust air duct, greatly improving the ventilation effectiveness. The mechanical air exhaust for the building greatly exceeded the outside air supply; as a consequence a relatively strong negative pressure existed in the building which caused some problems with backdrafting of the combustion equipment in the mechanical room. The excess of mechanical exhaust over outside air supply in the building likely helped to dry out the building.

4. With the exception of relative humidity, all of the three suites tested were able to meet the guidelines for indoor air quality with respect to carbon dioxide, formaldehyde, particulates, and volatile organic compounds. A considerable number of recycled materials were used in the building including kitchen cabinets. These aged materials generally have lower offgassing of formaldehyde and volatile organic compounds, and contributed to the good indoor air quality.

5. Energy consumption for space heating and ventilation increased following the retrofit, in large part because of the addition of the mechanical ventilation system with relatively large air flows. Another factor in the increased energy consumption is the full occupancy of the building post-retrofit compared with the pre-retrofit condition. Recommendations for reducing the ventilation rate and balancing the air flows are made in the report.

The rehabilitation of the building has improved the indoor air quality, the building aesthetics and longevity, and provided an improved living situation for low income people. Important data on moisture and heat transfer in an existing masonry building insulated on the inside with wood frame and glass fibre batt insulation were gained during the monitoring period. Based on the initial 15 months of data gathered, the moisture performance of the renovated building envelope has been satisfactory. Further monitoring of the building envelope is recommended to determine the moisture performance over a longer period of time.

RÉSUMÉ

La Société canadienne d'hypothèques et de logement a retenu les services de la section de la performance des bâtiments (Building Performance Section) du Saskatchewan Research Council (SRC) pour mener une recherche intitulée : Étude de cas portant sur la rénovation d'un immeuble d'appartements avec murs en maçonnerie massive. Situé à Prince Albert en Saskatchewan (Canada), le bâtiment, construit vers 1910 et rénové en 1996 et en 1997, comporte 4 étages et 30 logements. Il a été rénové en partie grâce au financement obtenu aux termes du programme PAREL de la Société canadienne d'hypothèques et de logement, afin d'augmenter l'offre de logements améliorés pour ménages à faible revenu.

L'équipe du SRC a collaboré étroitement avec les propriétaires, les représentants de la SCHL, le gestionnaire de l'immeuble, l'équipe de conception et avec les entrepreneurs à titre de conseiller, ainsi que pour documenter les travaux de rénovation.

Au cours des travaux, le bâtiment a été dégarni jusqu'aux murs de maçonnerie et jusqu'à la toiture, et on a aussi démoli et enlevé la dalle de plancher du sous-sol. De nombreux instruments et capteurs ont été placés dans tout le bâtiment de façon à pouvoir contrôler en continu la température, l'humidité relative, les différences de pression et finalement le milieu intérieur. Deux modèles de capteurs d'infiltration de l'eau de pluie ont été placés dans les murs extérieurs, à six endroits différents. La teneur en eau des solives dans le vide sous toit a également été contrôlée. Des fluxmètres thermiques ont servi à mesurer le mouvement de la chaleur traversant les murs. Aménagée sur le toit de l'édifice, une station météorologique a fourni des données climatiques, comme la vitesse et la direction du vent, les précipitations, la température, l'humidité relative et le niveau du rayonnement solaire. Tous les appareils de contrôle et de mesure ont été raccordés à un enregistreur chronologique multi-canaux, situé dans le bâtiment, qui a accumulé les données en continu à des intervalles de 30 minutes sur une période de surveillance de 15 mois. Environ 52 méga-octets de données ont été recueillies par l'enregistreur multi-canaux durant la période de surveillance, à savoir d'août 1997 à novembre 1998. Ces données serviront à contre-vérifier les modèles informatiques de transfert de chaleur et d'humidité dans les murs et pour évaluer la durabilité potentielle des murs. On a engagé un entrepreneur de Prince Albert pour prendre des photographies de la répartition du mouillage de l'enveloppe extérieure et pour relever les lectures des compteurs d'énergie et d'eau.

Le logiciel d'analyse énergétique HOT-2000 a été utilisé pour créer un modèle de l'utilisation d'énergie du bâtiment, modèle qui a dû être personnalisé, compte tenu de la taille du bâtiment. La consommation globale d'énergie a été quantifiée en mesurant la consommation d'électricité, de gaz naturel, et d'eau à l'aide de compteurs, au même titre que les quatre compteurs de gaz naturel additionnels mesurant la consommation des trois chaudières au gaz naturel et du chauffe-eau à gaz.

Les travaux de rénovation comprenaient la mise en œuvre des nouveaux éléments suivants : isolant du côté intérieur du toit et des murs, portes et fenêtres, pare-air/pare-vapeur de polyéthylène, fini de plaques de plâtre, revêtements de sol, système de ventilation, système de chauffage par rayonnement à partir des sols et membrane de toit. Contrairement aux trois autres élévations, la façade avant du bâtiment n'a pas été enduite de stucco, en raison du caractère historique de cette partie de Prince Albert.

Des essais de dépressurisation ont été réalisés à l'aide d'un ventilateur à débit contrôlé jumelé à des capteurs de pression localisés à mi-chemin dans le mur afin de déterminer le degré d'étanchéité de chacun des composants du mur.

La collecte de données en continu a révélé que le système de contrôle a maintenu un niveau d'intégrité très élevé au cours de la période de surveillance de 15 mois en plus d'être insensible aux perturbations électriques. D'ailleurs, les capteurs se sont avérés d'une fiabilité remarquable. Un modem a permis de contrôler les données à distance et de les télécharger du chantier aux bureaux du SRC à Saskatoon, à une distance de 150 km, ce qui a grandement amélioré la qualité des données recueillies.

Voici quelques-unes des principales constatations de l'étude :

1. Grâce à la mise en place du stucco sur les murs en maçonnerie, la probabilité que l'eau s'infiltre dans les murs a été réduite, comme en font foi les relevés des taux d'humidité dans les murs. Les surfaces enduites de stucco accusent une hausse des taux d'humidité causés par la pluie beaucoup moins importante que le mur de façade sans revêtement de stucco.

2. La comparaison entre les baisses de pression survenues à travers le mur de maçonnerie et celles survenues à travers l'ossature murale révèle que la grande majorité de l'étanchéité à l'air est fournie par le mur de maçonnerie massive. Il y a une couche de stucco du côté extérieur du mur de maçonnerie sur trois élévations tandis que du côté intérieur, tous les murs ont été enduits de crépi. Un mur à ossature de bois, doté d'un pare-vapeur de polyéthylène scellé a ensuite été érigé du côté intérieur. L'étanchéité à l'air globale du bâtiment s'est établie à 2,04 cm²/m², comparativement à 0,7 cm²/m² pour la norme R-2000.

3. Le nouveau système de ventilation mécanique a maintenu une bonne qualité de l'air intérieur dans les appartements et dans les aires communes. On a conçu ce système pour que chaque pièce des appartements soit munie d'un conduit d'évacuation d'air, ce qui a grandement amélioré l'efficacité de la ventilation. La quantité d'air évacuée par le système d'extraction excédait de beaucoup l'alimentation en air extérieur, ce qui a occasionné une forte pression négative dans le bâtiment, ainsi que le refoulement des gaz de combustion

des appareils situés dans le local technique. Cette évacuation excédentaire a fort probablement contribué à l'assèchement du bâtiment.

4. Sauf pour l'humidité relative, chacun des appartements faisant l'objet de tests était conforme aux directives d'exposition liées à la qualité de l'air intérieur se rapportant au dioxyde de carbone, au formaldéhyde, aux matières particulaires et aux composés organiques volatils. On a réutilisé un grand nombre de matériaux, notamment les armoires de cuisine. Ces vieux matériaux, qui dégagent habituellement moins d'émissions de formaldéhyde et de composés organiques volatils, ont contribué à la bonne qualité de l'air intérieur.

5. La consommation d'énergie pour le chauffage des locaux et la ventilation ont augmenté à la suite des travaux de réfection, en raison principalement de l'addition du système de ventilation mécanique qui comportait des débits d'air relativement importants. Un deuxième facteur a trait à un taux d'occupation maximal du bâtiment par rapport au taux d'occupation précédant les travaux d'amélioration. Le rapport fait état de recommandations visant à réduire le taux de ventilation et à équilibrer les débits d'air.

La restauration du bâtiment a amélioré la qualité de l'air intérieur, son apparence et sa durabilité, et a fourni aux ménages à faible revenu de meilleures conditions de vie. Durant la période de contrôle, des données importantes ont été recueillies sur le mouvement de l'humidité et de la chaleur dans un bâtiment existant en maçonnerie qui a été isolé par l'intérieur à l'aide d'une ossature de bois et de nattes d'isolant en fibre de verre. Si l'on se fonde sur les données initiales recueillies sur une période de quinze mois, le rendement de l'enveloppe du point de vue de l'humidité a été satisfaisant. Par ailleurs, il est recommandé de mettre sur pied un programme de surveillance à long terme afin de mesurer les effets de l'humidité sur l'enveloppe.

1.0 INTRODUCTION

This is the final report on the renovation of an apartment building located in Prince Albert, Saskatchewan.

The original building, constructed in approximately 1910, underwent a major renovation in 1996 and early 1997. The building was in great need of repair. The following are some excerpts from an inspection report dated March 13/14, 1996 prior to the renovation.

- "There is evidence of (roof) leakage and the roof requires repair/replacement."
- "While the building exhibits no obvious structural problems, separations, deterioration of mortar joints and general wear were observed on the exterior brick."
- "The overall interior condition of the unit is very poor and will require significant rehabilitation to bring it to a standard acceptable to the City of Prince Albert and the Prince Albert Health District, Public Health Unit."
- The Public Health Inspector has "issued an order to vacate all basement suites, contract the services of a pest control operator to abate the cockroach infestation, and remove garbage and debris and appliances from the property. As apartments are vacated they will be placarded as unfit for human habitation."
- "Tenants on the first level were to be evicted and repairs throughout the building must be completed by a specified date...."
- "The project is in very poor condition. The odour throughout the building was palpable (mildew and mold, etc.) even though a lot of the debris had already been removed prior to my inspection...."
- "The owners' representative advised of intentions to upgrade by adding insulation to the interior of the exterior walls. Since it is difficult to maintain the continuity of the vapour barrier as well as thermal values due to intersecting walls and dropped ceilings, etc., this methodology could negatively impact performance of the exterior wall and in particular the brick exterior. It is therefore recommended that professional advice, (Building Scientist), be sought prior to proceeding with any thermal upgrade, to determine the most practical and effective thermal upgrade method. "

The owners successfully applied to CMHC for a Rental RRAP loan for the renovation.

The renovation included addition of an interior wood stud wall with approximately RSI 3.5 batt insulation, additional roof insulation, a polyethylene air- vapour barrier, air sealing, new gypsum board, new windows and doors, a mechanical ventilation system with ventilation provided to each room, a new radiant floor heating system for the upper three floors, a new roof membrane, new finish flooring, and the addition of stucco over three of the existing brick walls of the building.

A photo of the building exterior during the rehabilitation is shown in Figure 1, and a photo of the completed building is shown in Figure 2. The most visible change to the outside of the building is the addition of stucco to the back (west, east, and south) three sides of the building. The stucco improved the appearance of the building through covering cracks and other cosmetic problems; in addition, the stucco has assisted in shedding rainwater on the back three sides of the building. The front elevation of the building did not have stucco applied because of heritage appearance considerations. The building is located in an area of Prince Albert with other heritage buildings. The interior renovations and installation of a continuous mechanical ventilation system have greatly improved the aesthetics and the indoor environment of the building.

A contract was awarded to the Saskatchewan Research Council in 1996 with the following objectives:

- To document an entire retrofit strategy for a multi-unit residential building with solid masonry walls
- To monitor and assess the performance of the building envelope retrofit over the period of one year
- To monitor and assess the indoor air quality within the suites of the renovated building
- To monitor the energy performance of the building after the envelope retrofit and to compare it to the pre-retrofit performance
- To generate a case study document that details the before and after condition and describe the performance of the building

Four interim progress reports have been issued for the project.

Report 1 was issued in March 1997 and included the following.

1. Information on evaluating rain penetration through the existing masonry walls.

   A water spray rack was used to determine the rate at which water would penetrate through the existing brick wall on the fourth floor of the east wall. A test was conducted starting at 8:35 a.m. on August 29, 1996. The water spray had an average flow intensity of 12 litres per minute per square metre of wall surface. Water was found to penetrate through the brick wall 54 minutes later. An aluminum box with a surface area of 0.5 square metres had been attached to the interior of the brick wall and a negative pressure of 10 pascals applied to the box to simulate the effect of a driving rain. It was found, however, that moisture also penetrated other parts of the wall where the flow box was not attached, indicating that the negative pressure in the box had little effect on the water penetration through the wall.

2. Evaluating the bond between a proposed stucco and the existing masonry walls.
   The need for a surface primer to assist in reducing the probability of weak spots, leading to debonding and a progressive delamination of the stucco from the clay brick surface was evaluated using twelve different Instron tests of stucco, and brick with and without a surface primer. The surface primer was found to be of value and was used on the building.
3. Evaluating the cracking propensity of the base stucco.
   Samples of stucco were prepared and applied to wood planks 19 mm thick, and 200 x 250 mm in length and width. The wood was primed with a surface primer (polyvinyl acetate emulsion) and a base coat of stucco (6 parts sand, 2 parts standard Portland cement, 1 part lime, water and ½ cup of fibre reinforcement) was applied. Specimens were exposed to water immersion and infrared lamps to simulate flexing. Based on the testing, the following measures were recommended for the stucco:
   - use "weldbond" admixture in all applications of the base coat of the stucco
   - make a schematic drawing of all major cracks in the masonry (they were mostly in vertical lines starting at the place where the window sill plate ends)
   - immediately after applying the scratch coat, roll into the scratch coat about 20 cm wide strip of the fibreglass mesh used for reinforcement of the External Insulation Finishing System stucco applications
   - make each day's work to be completed from one expansion joint to another
   - an expanded metal lath was recommended as a reinforcing strip around all windows
4. Pressure test results on the initial room air/vapor barrier installation.
   Pressure testing was done on one suite that had the room air/vapor barrier installed, but without the gypsum board applied. It was found that the quality of the installation was for the most part good, but that there were leakage spots at the ceiling level where the upper floor intersects the outside wall. It was recommended that an infrared camera be used in future work of this type to better isolate leakage spots.
5. A description of the monitoring used in the project, including the data logger, and a list of sensors and monitoring equipment.
   A complete description of the monitoring equipment used was presented. Six locations on the exterior walls were chosen. The locations were as follows

Monitoring Locations in Exterior Walls

Monitoring Locations	Floor Level
NW1 Northwest Corner	1
W2 West Wall	2
E3 East wall	3
N4 North wall	4
NW4 Northwest Corner	4
SE4 Southeast Corner	4

At each wall location, sensors were used to provide 6 temperatures across the wall, 2 pressure differences (across the brick wall and across the stud wall), 2 heat flux transducers (lower wall and upper wall), and a relative humidity sensor (between the brick wall and the glass fibre batt insulation)

Wood moisture pins were placed at the ends of three joists resting in the north brick wall. Moisture pins were also placed at three locations in the attic joists. Rain penetration sensors developed by SRC were placed at the six wall locations mentioned in the above table; the sensors were located one brick out from the inner part of the brick wall. Onysko wood moisture sensors were also placed adjacent to the SRC sensors.

A weather station with horizontal solar radiation, wind speed and direction, outdoor temperature and relative humidity, and a rain gauge was placed at the center of the roof. In addition, rain gauges were located above the NW and SE walls of the building.

Report 2 was issued in September 1997 and included the following.

1. Preliminary plots of the readings from the data logger.
   The data logging system for the building was fully commissioned on August 15, 1997. A total of 101 sensors had been connected to the data logger. Data was stored at half hour intervals, and the data was downloaded on a weekly basis by modem. Nine plots were prepared for the interim report, indicating that the data was satisfactorily being recorded, and that all the data points were properly being recorded.
2. A full description of all the data sensors and the monitoring intervals was reported.

Report 3 was issued in February 1998 and included the following.

1. Sensor calibrations for the data logging system. Calibrations were made of the 12 types of sensors used on the data logging system.

   The pressure transducers are prone to drift. The zero drift was measured on the 12 pressure transducers measuring wall pressure differences in November 1997. The zero drift values were modest, with the maximum drift equal to 1.1 pascals on sensors that have a 0 to 250 pascal range. The transducers were re-zeroed. The outputs of the other sensors were checked to see that reasonable values were being recorded.

2. Neutral pressure level measurements for the building were reported.

   Normally the neutral pressure level in a building will be approximately at the mid-height of the building if the air leakage locations are evenly distributed vertically, the wind speed is negligible, and the air handling system for the building supplies equal quantities of outside air and exhaust air flows. Using the wall mounted pressure transducers during a period with no wind, it was determined that the neutral pressure level was above the top of the building; in other words, the mechanical system air flows were such that the exhaust air greatly exceeded the outside air supply flow for the building. The exhaust air supply was 1159 L/s and the supply air flow was 775 L/s, according to the air balancing firm's report.

3. A description of the odour problem in the furnace room was presented along with a recommended solution to the problem.

   Because of the excess of exhaust air over supply air for the building, there was some backdrafting of the combustion equipment in the building, most often during the start of the firing cycles for each of the boilers and water heater. Air leakage into the filter section of the outside air supply for the building also contributed to the backdrafting. The filter was located on the negative pressure side of the outside air supply fan, and air leakage through the filter housing was a problem. A recommendation was made to rebalance the supply and exhaust air flows to the building and remedy the leakage of air into the filter section. The latter recommendation was implemented.

4. Measurements of the relative pressure drops across the brick wall and the stud walls at the six locations were presented.

   The location of the effective air barrier in the wall was of interest. Using the pressure transducer data, it was determined that the brick wall (including the stucco and parging) had a pressure difference that ranged between 75% and 92% of the total exterior wall pressure difference.

5. Preliminary energy readings from the apartment complex, including electrical energy use and natural gas use, were presented along with the heating degree day values.

   Electrical energy consumption in the individual suites varied from a low of 0.3 kWh/day for an unoccupied suite used as a games room, to a high of 12.4 kWh/day, with a median consumption of 5.3 kWh/day and an average of 5.6 kWh/day. Insufficient data had been gained from the natural gas use at that time to make any firm projections about annual use.

Report 4 was presented in June 1998. In that report the following items were covered.

1. Discussion of the HOT 2000 computer model that was developed for the building.
   Results from the HOT 2000 computer model were presented. The HOT 2000 model was a special version of the HOT 2000 residential program that could accomodate the large volume and air flow rates found in the building.
   The largest component of heat loss in the building was the ventilation and air change component.

2. A preliminary comparison was made of the measured energy consumption data for the facility with the computer prediction.
   The monthly natural gas consumption values as estimated by the computer model for the building were found, as expected, to be linearly related to the outdoor heating degree-days per day values. The measured natural gas consumption of the building, using data from December 1997 to March 1998, was lower than the computer model projections by about 25%.

3. Indoor environment measurements.
   Measurements were made of the formaldehyde, particulates, volatile organic compounds, carbon dioxide , indoor temperature, relative humidity and ventilation rates in three suites of the building between February 11 and February 25, 1998. With the exception of relative humidity, which was low in all the suites because of the high ventilation rates and the absence of humidification, the indoor air quality values all met recognized guidelines.

Copies of the four interim reports are attached in Appendix I.

In this the final report, the following material is covered:

1 Description of the data logging readings including the graphs of the various individual points.
2. Measured energy consumption compared with the computer model.
3. Wetting patterns and weather conditions.
4. Recommended changes to the building to improve performance.

2.0 OBSERVATIONS

A Sciemetric System 200 Data Logger was used to record values from the various sensors located in the building. The intent of the data logging was to continuously monitor the heat flow and moisture performance of the retrofitted walls (6 locations) and attic, to document the interior conditions of relative humidity and temperature, and to monitor the outdoor conditions of temperature, relative humidity, wind speed and direction, horizontal solar radiation, and rain fall on the roof. Information from the data logging would be used to provide information on the performance of the retrofitted building envelope and the interior conditions in the building. In addition, the data would later be used in a computer model for building envelope moisture and heat flow performance at the Institute for Research in Construction of the National Research Council of Canada.

The following sets of graphs were generated using data accumulated by the data logger. A modem hookup was used between Prince Albert and Saskatoon to download the data on a weekly basis. The modem hookup also facilitated identifying any sensor failures during the monitoring. For instance, an electrical connection inside the solar radiation sensor failed; weekly checks of the data identified this error, and repairs were able to be made.

Overall, the data integrity from the readings was very high. Readings were taken and averaged every half hour continuously from August 29, 1997 to November 19, 1998. A total of 21,600 points was recorded and plotted for each of the sensors (two readings/hour x 24 hours/day x 450 days.) The data were recorded in ASCII files and then transferred to a Quattro Pro Spreadsheet. The spreadsheet is 52 Megabytes in size, and because of the large size, a CDROM containing the data was produced.

2.1 Weather Conditions

The following outdoor conditions were monitored: temperature, relative humidity, wind speed and direction, horizontal solar radiation, and rain fall. These sensors were all located on the roof. The wind speed indicator was located 3.0 metres above the roof surface.

In Figure 3 a plot of the outdoor temperature measured by a weather station on the roof of the building is presented. As can be seen the peak temperature reached +30°C and the minimum temperature was -34°C. A very large change in temperature occurred at Day 366 (January 1, 1998) when the outdoor temperature fell precipitously in a very short period of time. At that time a high pressure Arctic front moved into the area, and displaced warmer Pacific air. The prairie climate is strongly influenced in Winter by the movement of frontal systems from the Arctic.

Over the 15 month monitoring period, the measured Environment Canada heating degree-day values are compared with the long term (30 year) averages in Table 1.

Table 1. Comparison of Actual and Long Term Heating Degree Days–Prince Albert Airport

Month	Actual Heating Degree Days (base 18 °C)	Long Term Average Heating Degree Days (base 18 °C)
August 1997	56.2	81.7

September	164.4	243.6
October	463.9	444.1
November	682.1	767.9
December	744.7	1085.8
January 1998	1156.8	1175.9
February	675.7	960.7
March	800.4	833.5
April	342.3	461.9
May	178	240
June	119.8	97.8
July	26.4	43.9
August	22.7	81.7
September	181.9	243.6
October	434.4	444.1
November	710.4	767.9
Totals	**6778.1**	**7992.1**

As can be seen from Table 1, the months of the monitoring had considerably fewer heating degree-days than the long term average. The winter season of 1997-98 was dominated by the El Nino phenomenon.

Figure 4 presents the average wind speed as measured by an anemometer located on the roof of the building. The peak average wind speed measured over a half hour interval was approximately 27 km/hr and the minimum was 0 km/hr over the monitoring period. The average wind speed was 7.5 km/hr with a standard deviation of 4.4 km/hr.

Figure 5 presents the horizontal solar radiation as measured by a global pyranometer located on the roof of the building. The peak horizontal solar radiation measured over a half hour interval amounted to 975 watts per square meter. The peak occurred on Day 528, which would correspond to June 12, 1998. From approximately Day 550 until Day 600 the solar radiation sensor was giving an intermittent reading. Because of this problem, the sensor was removed and a solder joint internal to the sensor was repaired.

Figure 6 presents the outdoor relative humidity measured by a thin film capacitance sensor located on the roof of the building. The output varied from a high of 100% to a low of approximately 12%. A relatively large daily fluctuation occurs because of the daily temperature fluctuations.

Figure 7 presents the absolute humidity measurement of the outside air. The absolute humidity was calculated based on the outdoor air temperature and the outdoor relative humidity. The absolute humidity reaches a very low value during cold weather. As can be seen, after day 365 (December 31, 1997), the absolute humidity drops almost to zero in that very cold spell. In the warm weather the absolute humidity rose to a peak value of 16 grams of water per kilogram of dry air at approximately Day 555 (July 9, 1998). This large difference in absolute humidity from winter to summer is characteristic of a continental climate such as is experienced in Prince Albert.

Figures 8 through 15 present the wind direction frequency on a half hourly basis over the monitoring period. As can be seen from the diagrams, the wind is from all directions. As was noted earlier, the wind speed is relatively modest in Prince Albert. Prince Albert is located on the southern end of the Boreal forest in Saskatchewan.

Photos of the weather station and one of the rain gauge installations are shown in Figure 18.

In most of the Canadian Prairies, rainfall is usually, but not always, accompanied by easterly winds.

On the northwest corner of the roof as shown in Figure 16, the peak rainfall on Day 553 (July 7, 1998) was 17 mm. On the southeast corner of the roof as shown by Figure 17, the rainfall was 21 mm for that half hour period. In the center part of the roof (Figure 19), the peak rainfall recorded in a half hour period was 25 mm. These rainfall numbers indicate that a considerable variation can exist in the rainfall received at various locations on the roof of a building. As shown in Figure 18, there exists a relatively taller parapet on the north side of the building which would affect the air flows in the vicinity of the northwest rain gauge. Another day with relatively high rainfall was Day 540 (June 24, 1998). The center part of the roof received a peak of 17 mm of rainfall in a half hour period, the northwest corner received 15 mm, and the southeast corner received 17 mm.

The monthly rainfall, snow, and total precipitation values as recorded by Environment Canada for Prince Albert over the monitoring period were as follows:

Appendix 1

Interim Reports on the Project

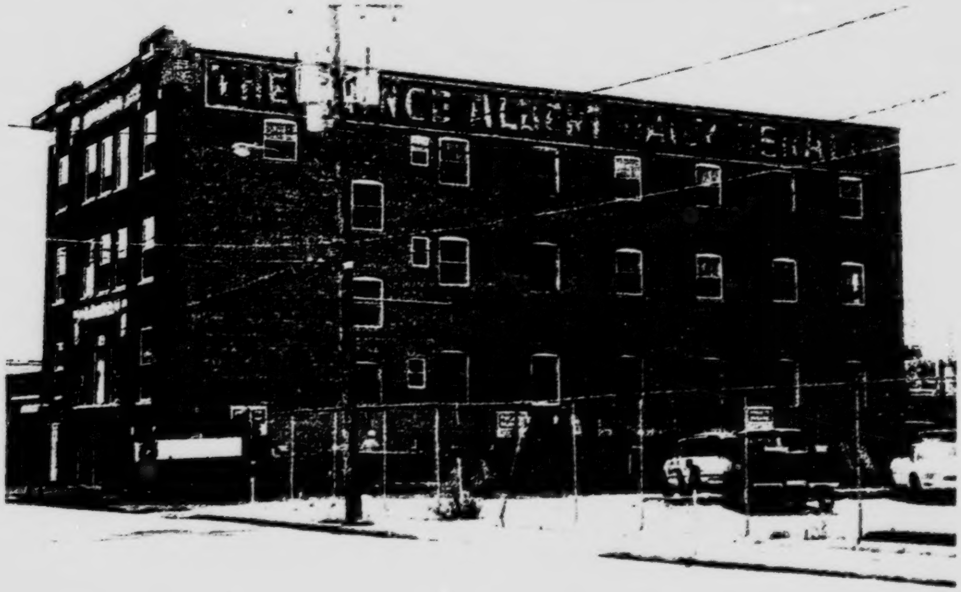


Figure 1. View of the apartment building during rehabilitation (from the Northwest)

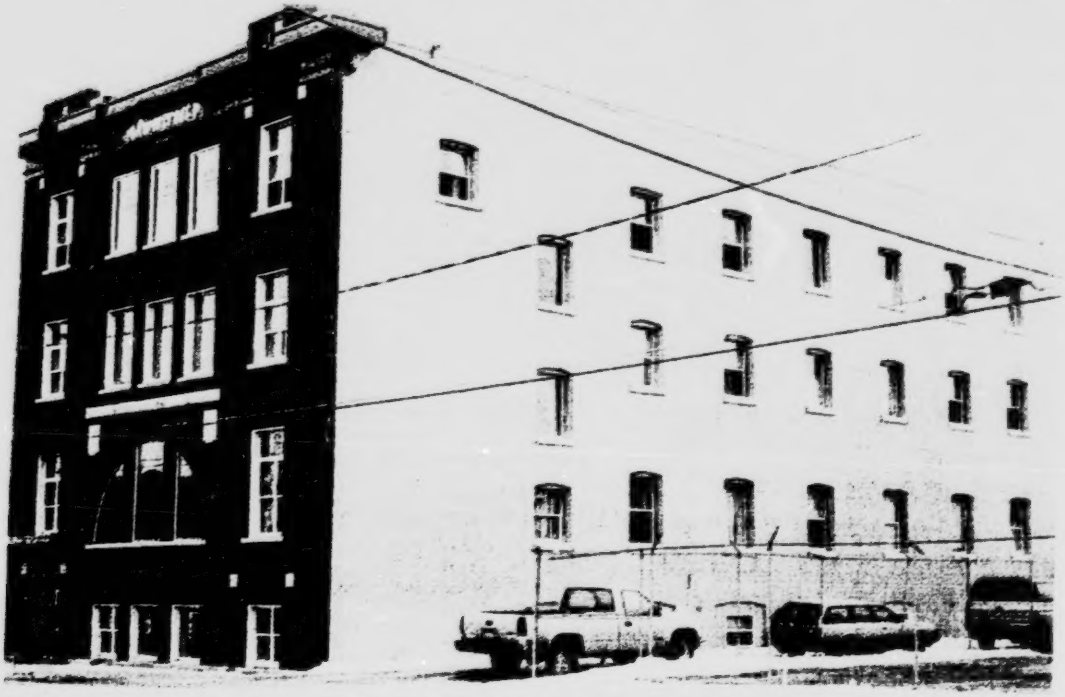


Figure 2. View of the apartment building following the retrofit (from the Northwest

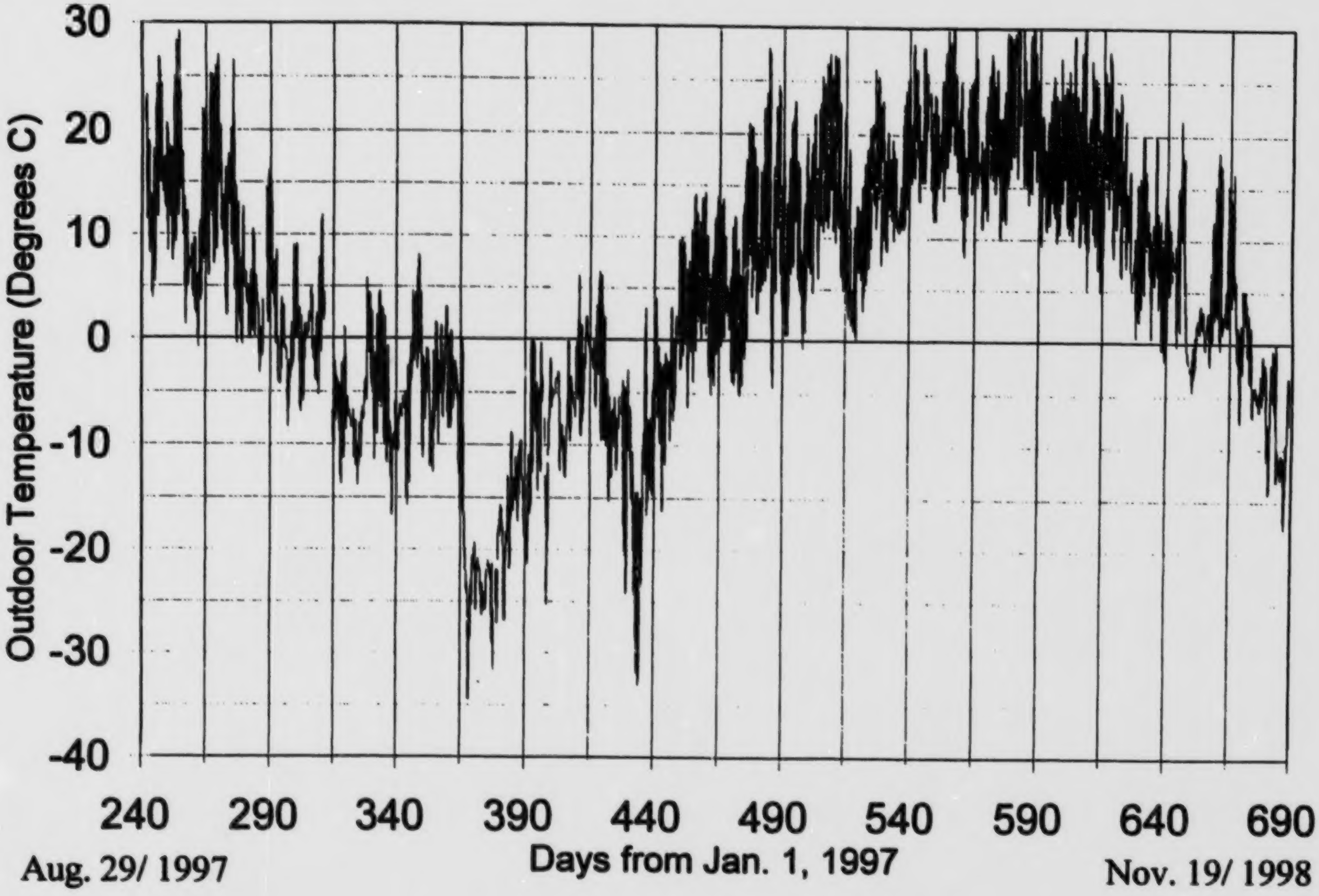
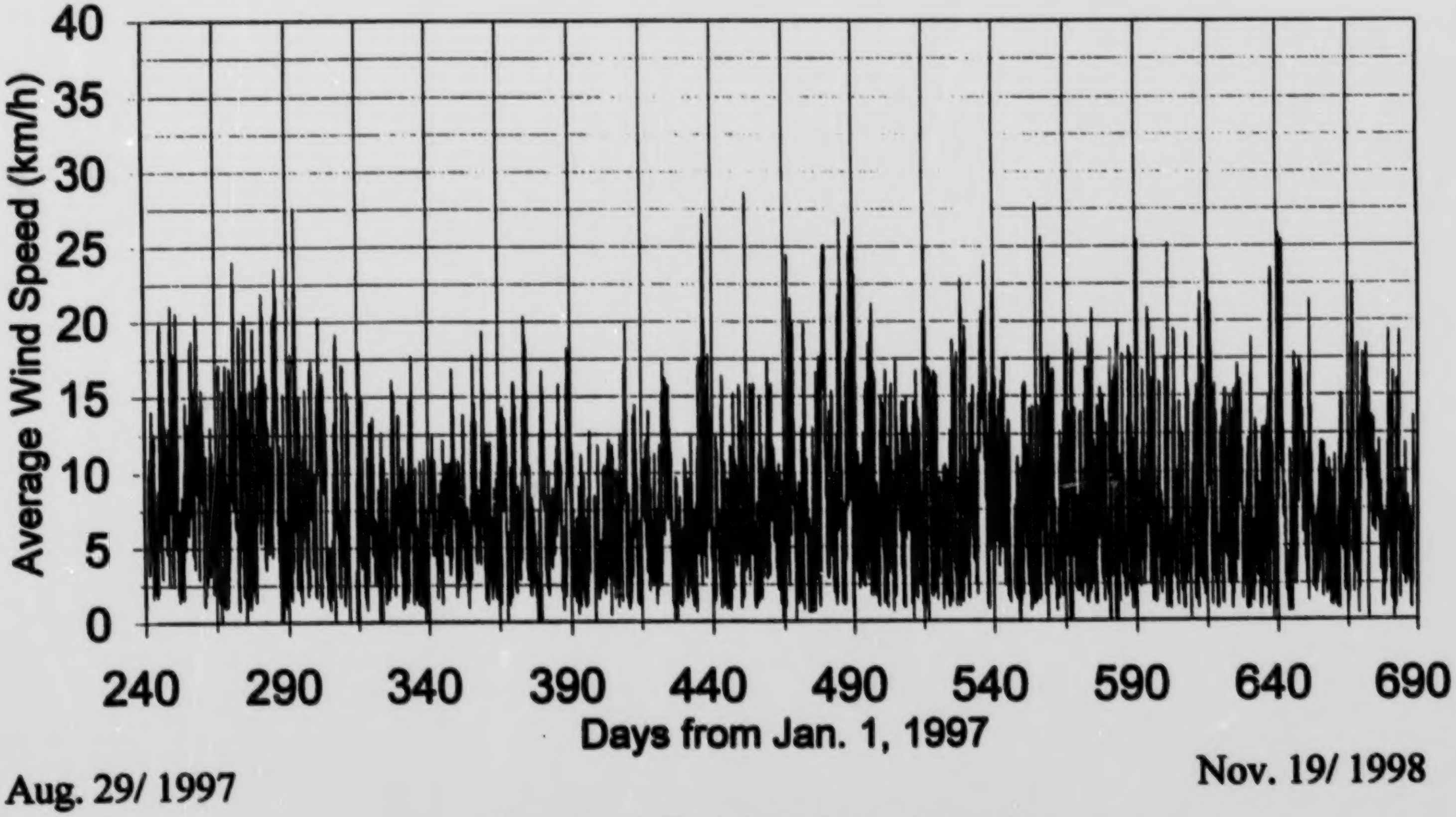


Figure 3. Outdoor temperature over the monitoring period.



Average Wind Speed = 7.48 km/h

Standard Deviation = 4.37

Figure 4. Average wind speed over the monitoring period as measured by the anemometer on the roof of the building.

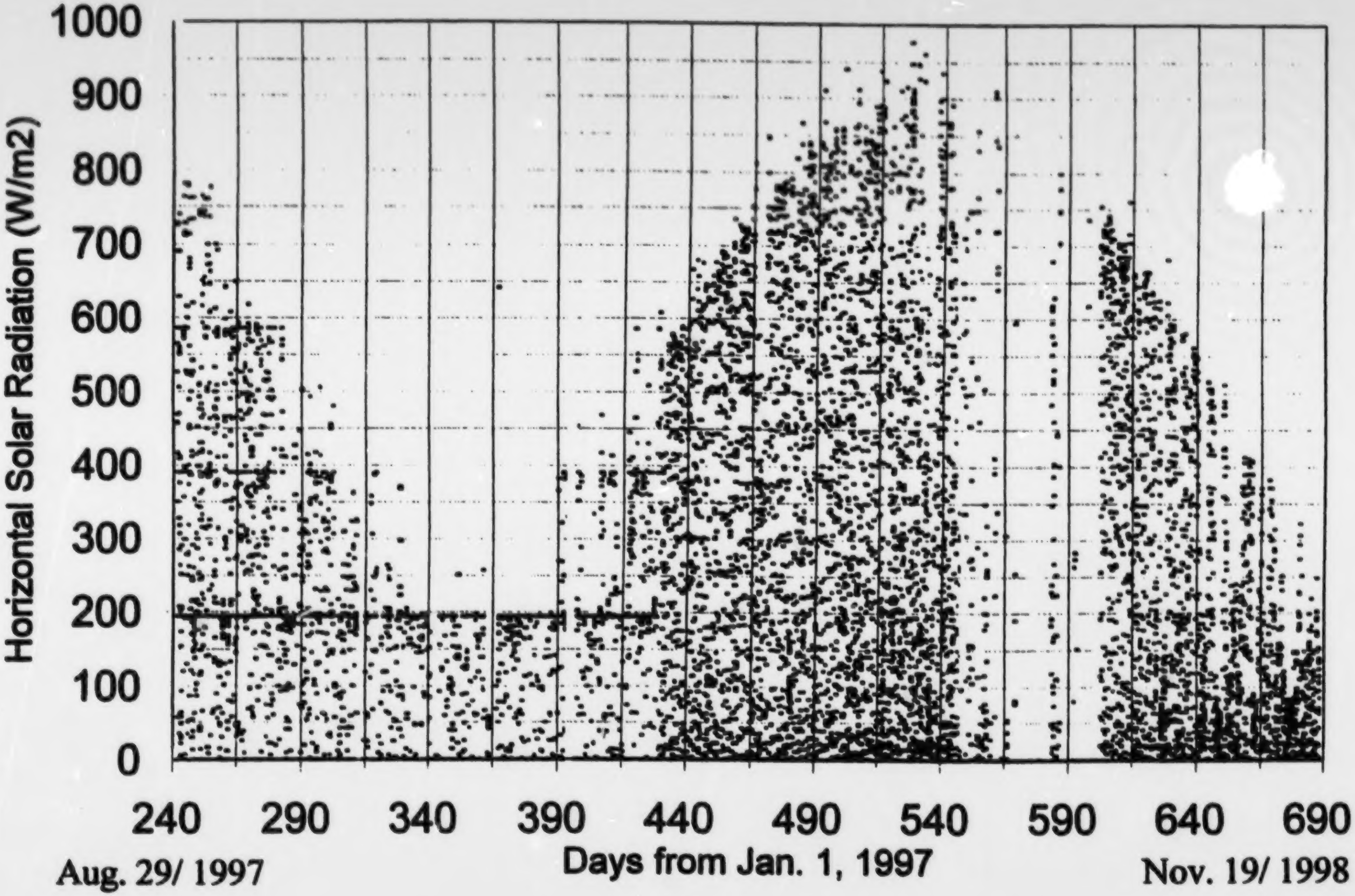


Figure 5. Global solar radiation over the monitoring period.

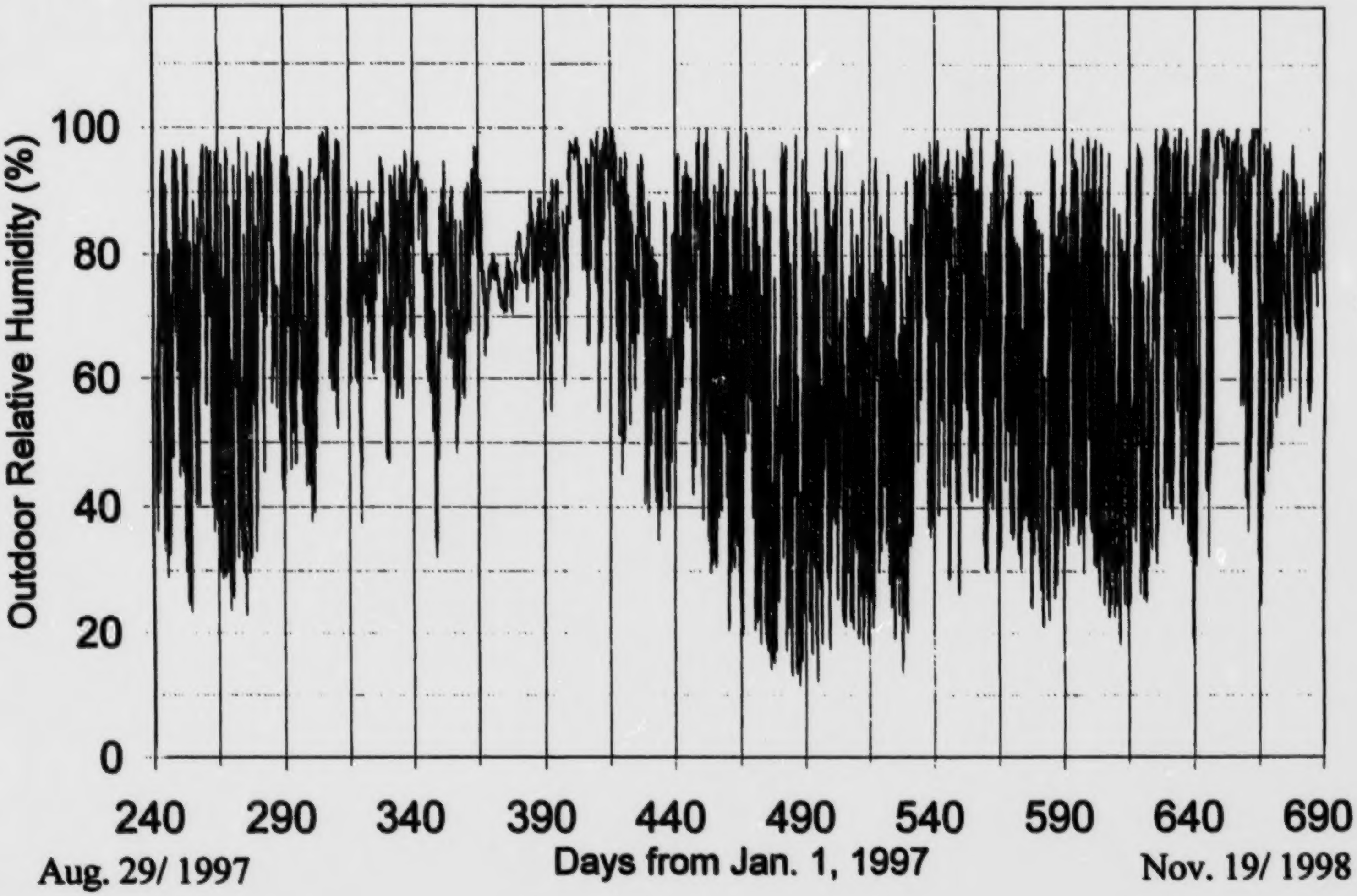


Figure 6. **Outdoor relative humidity.**

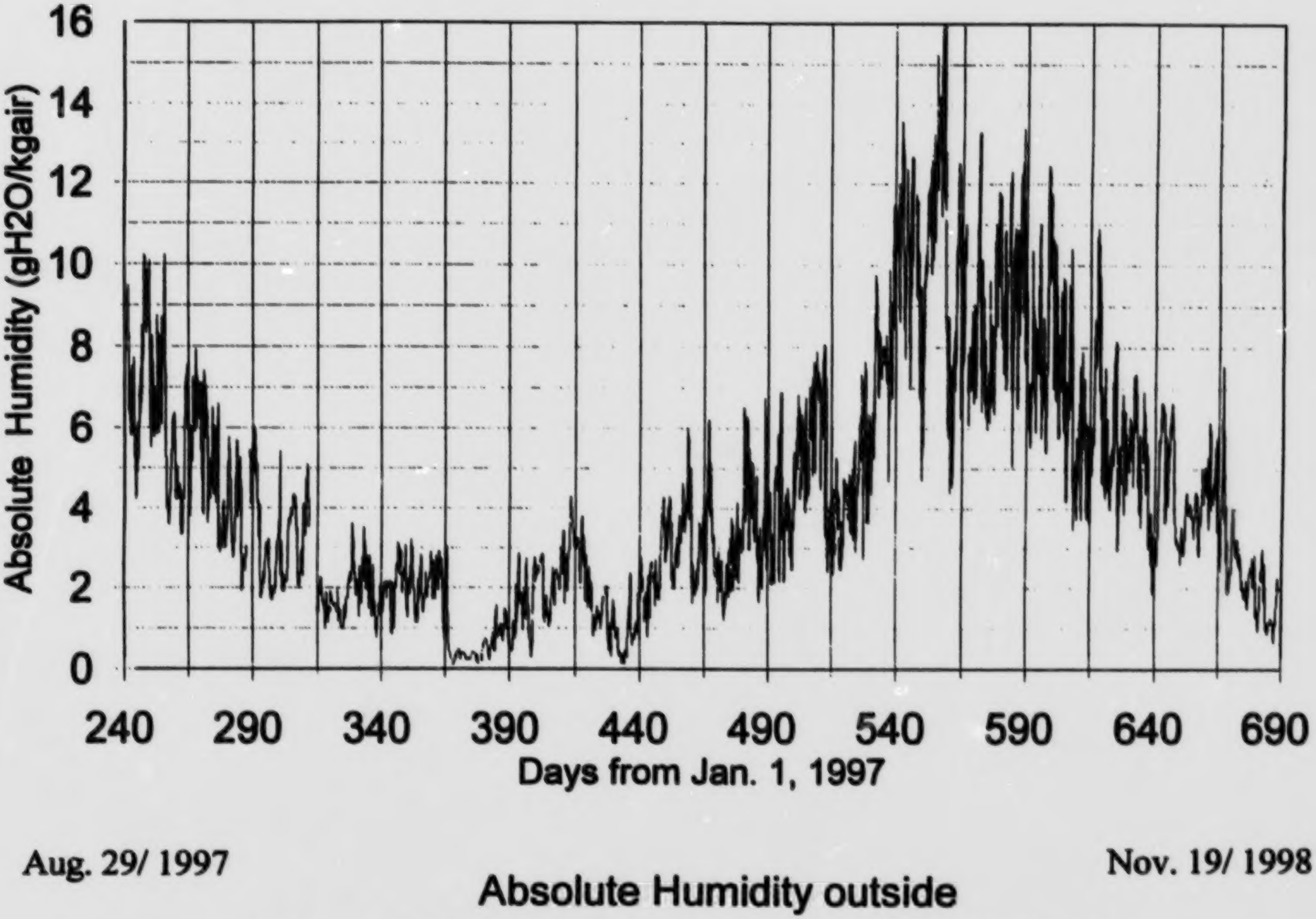
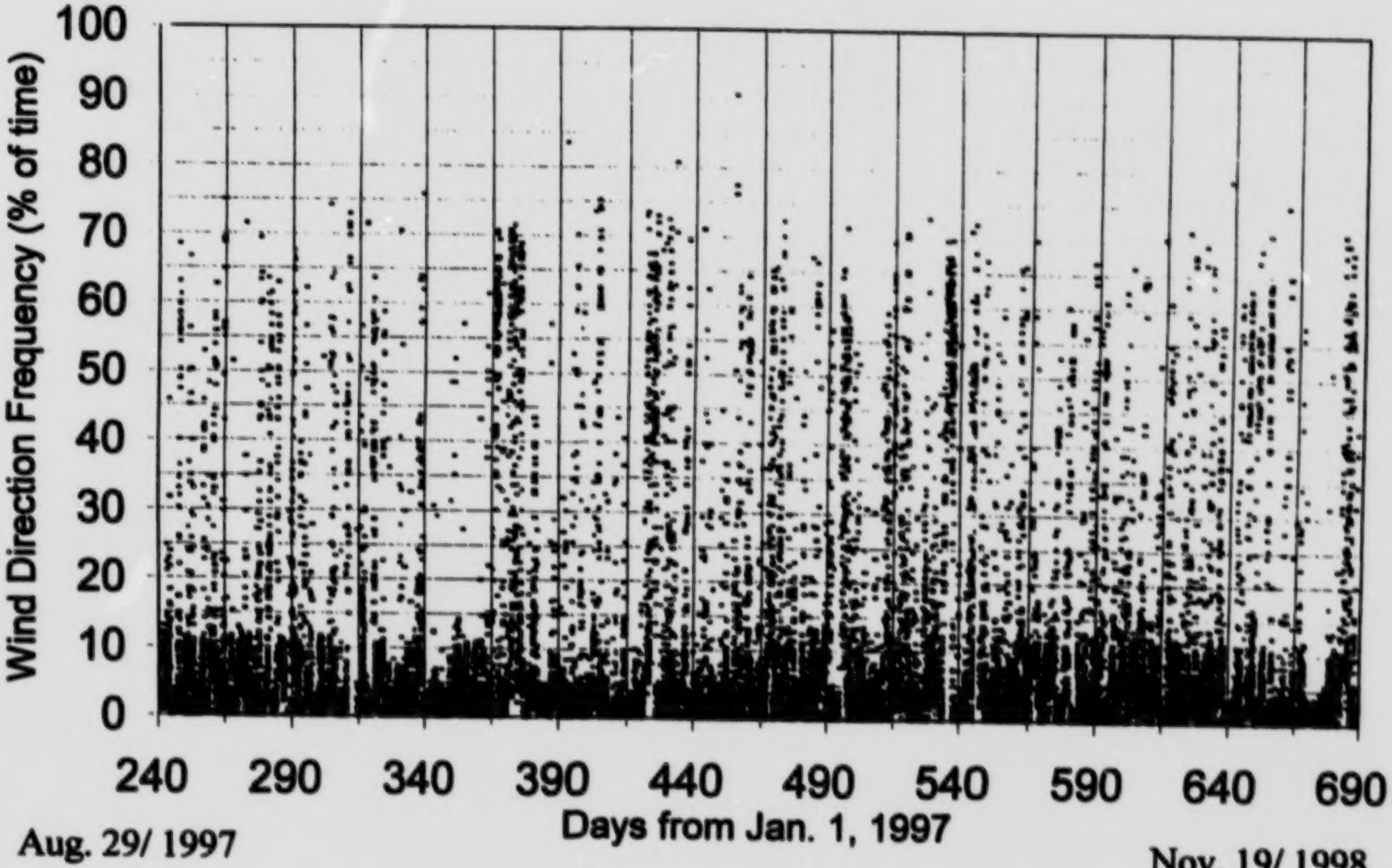


Figure 7. Outdoor absolute humidity. (Calculated from the relative humidity and temperature readings.)



"North (337.5 to 22.5 degrees from N)"

Figure 8. Wind direction frequency for north direction.

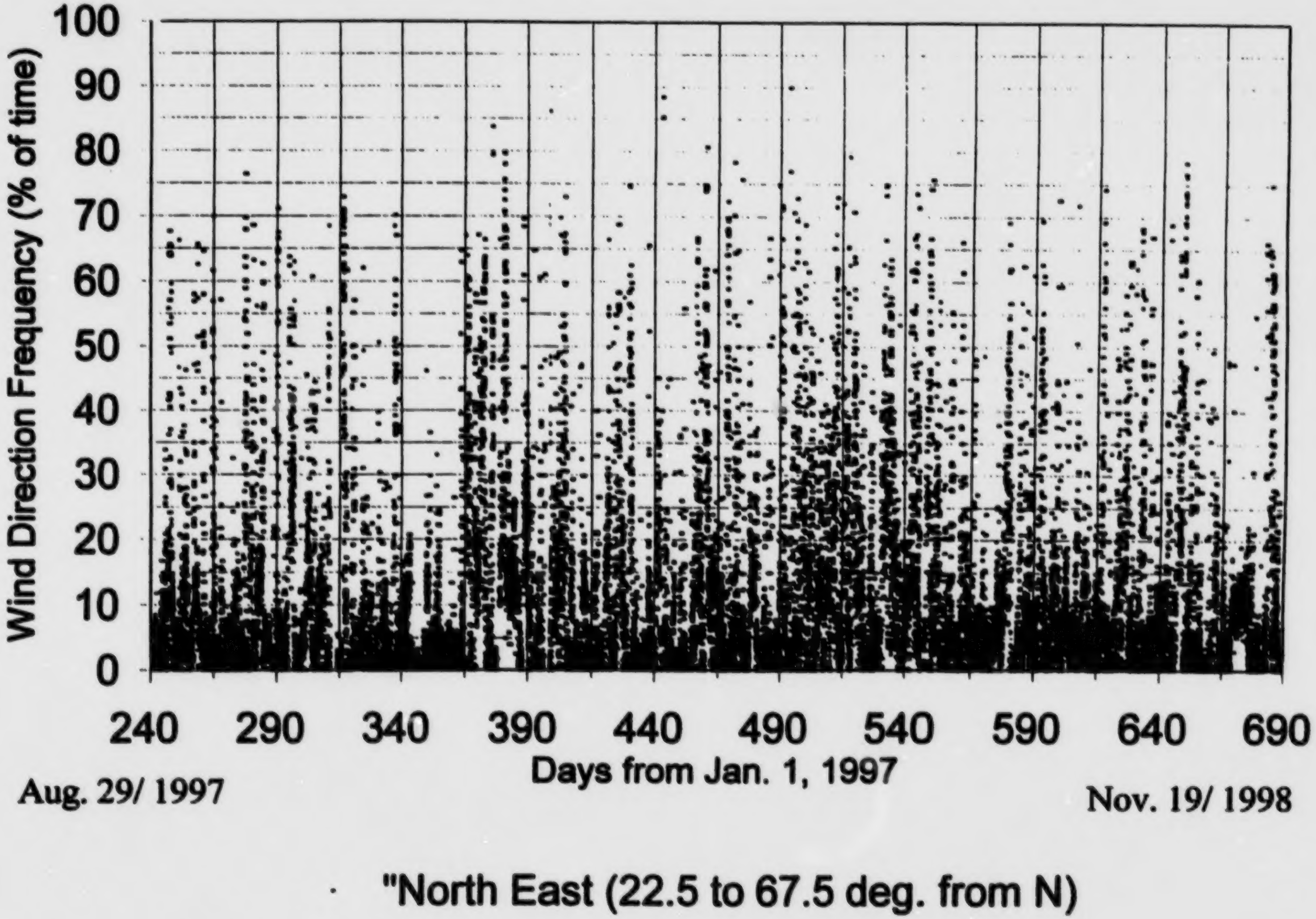


Figure 9. Wind direction frequency for northeast direction.

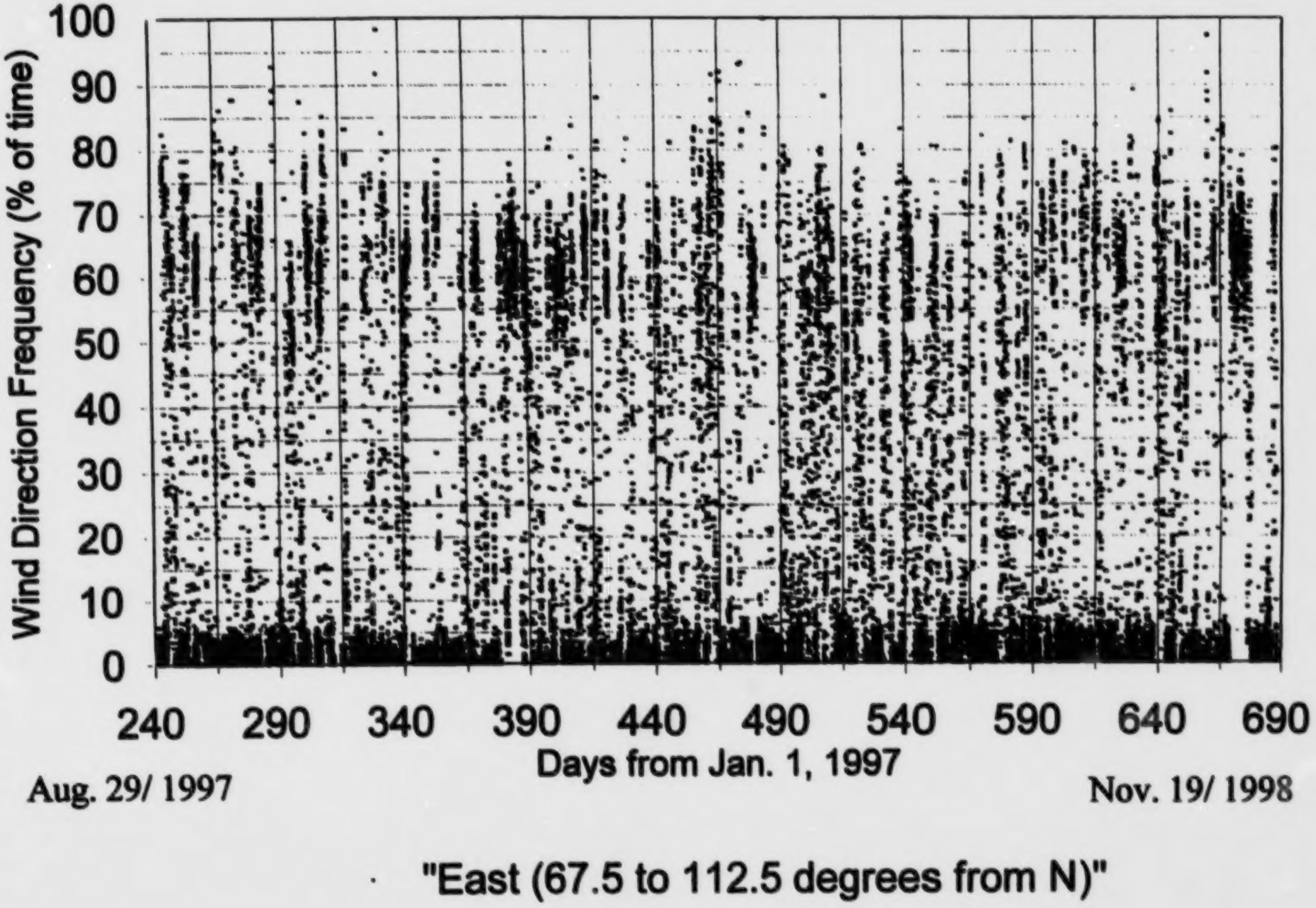


Figure 10. Wind direction frequency for east direction.

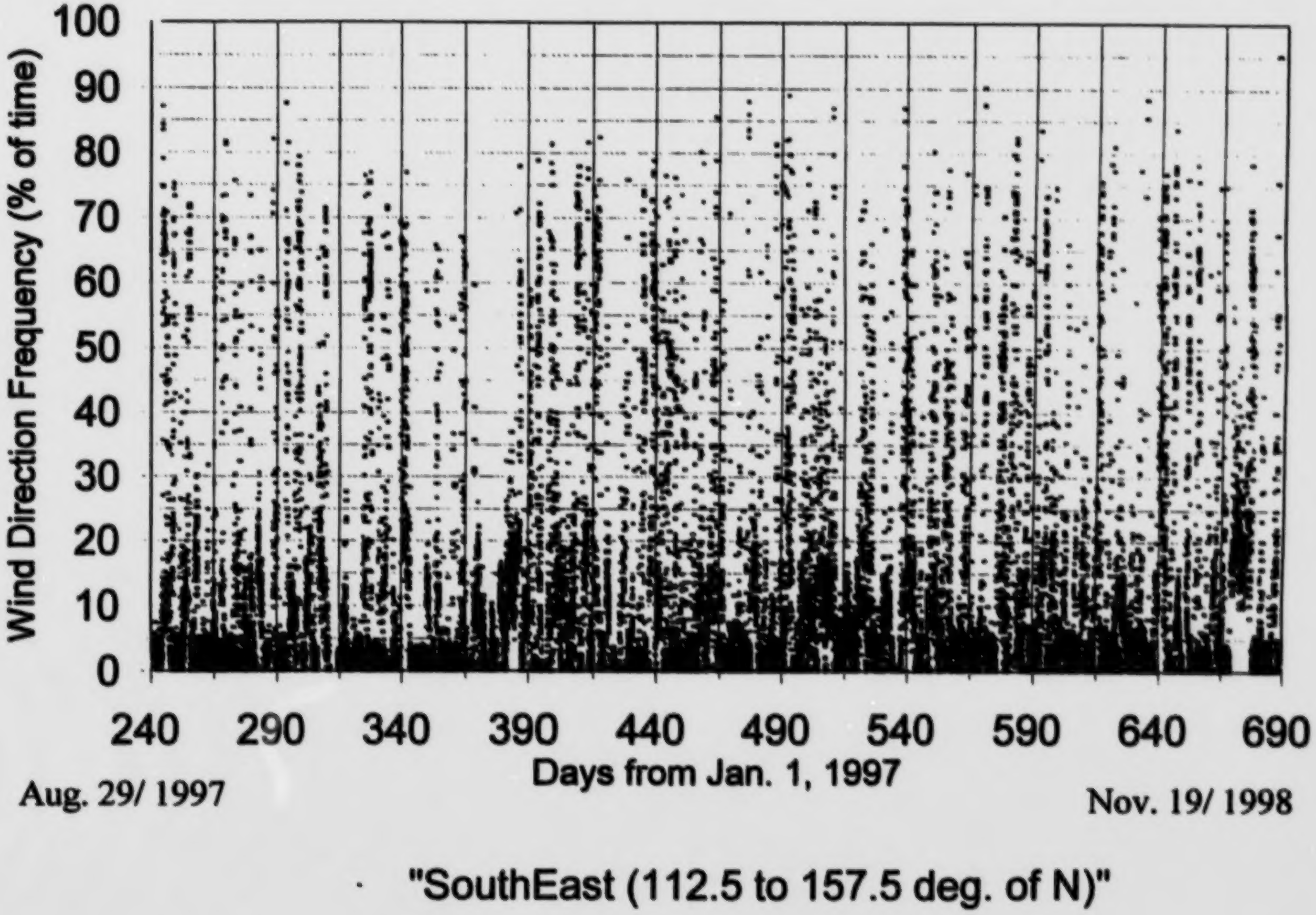


Figure 11. Wind direction frequency for southeast direction.

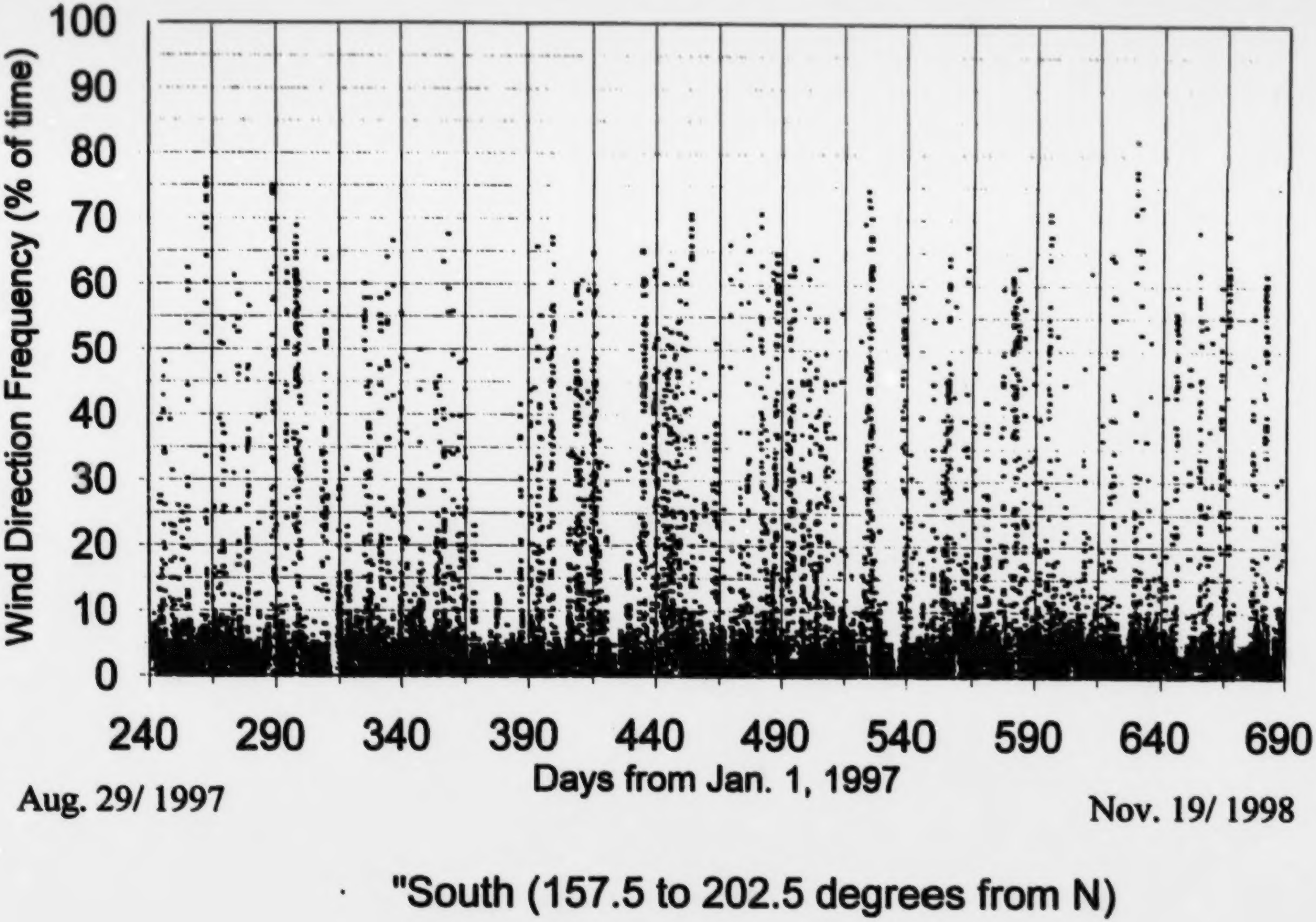


Figure 12. Wind direction frequency for south direction.

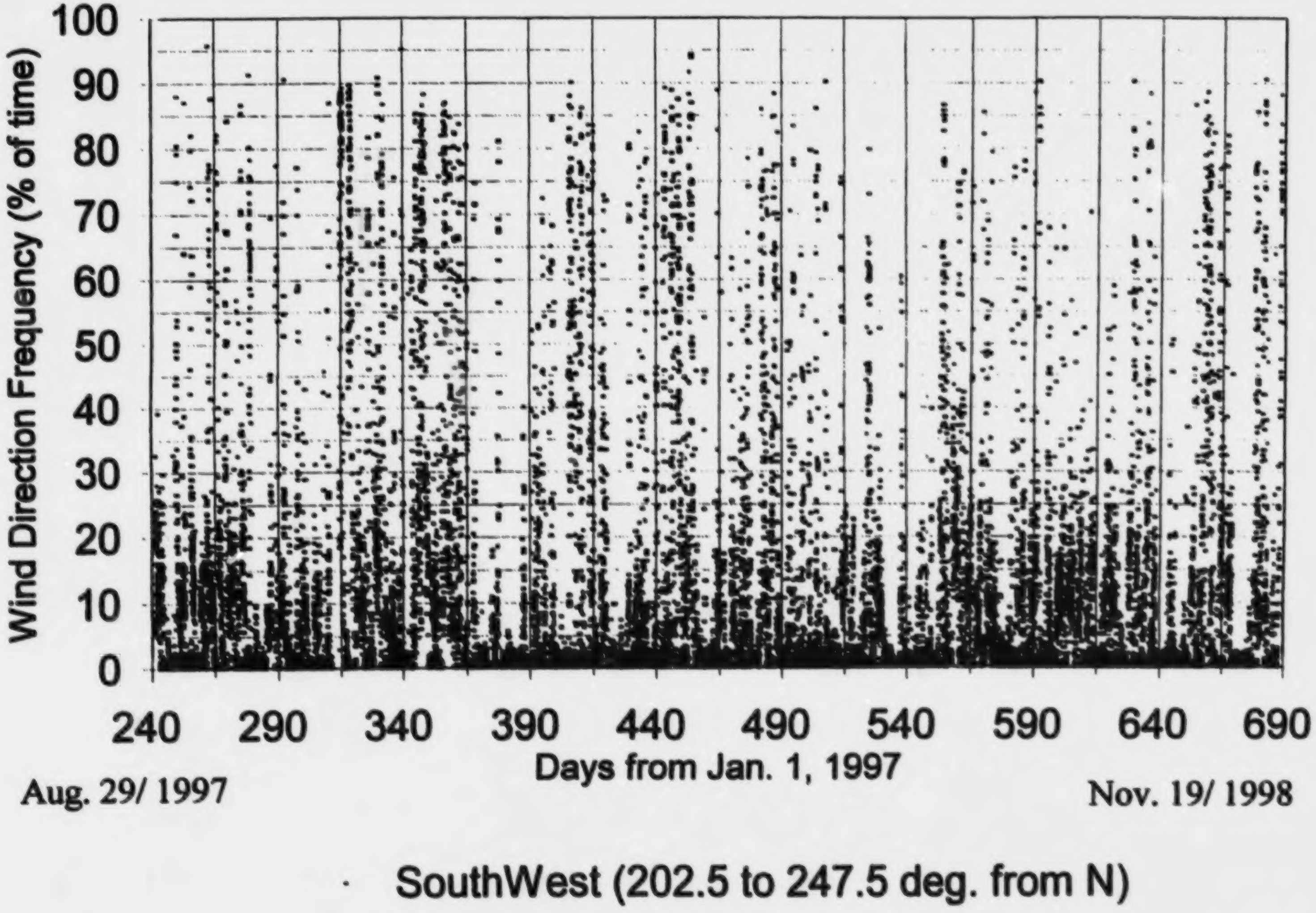


Figure 13. Wind direction frequency for south west direction.

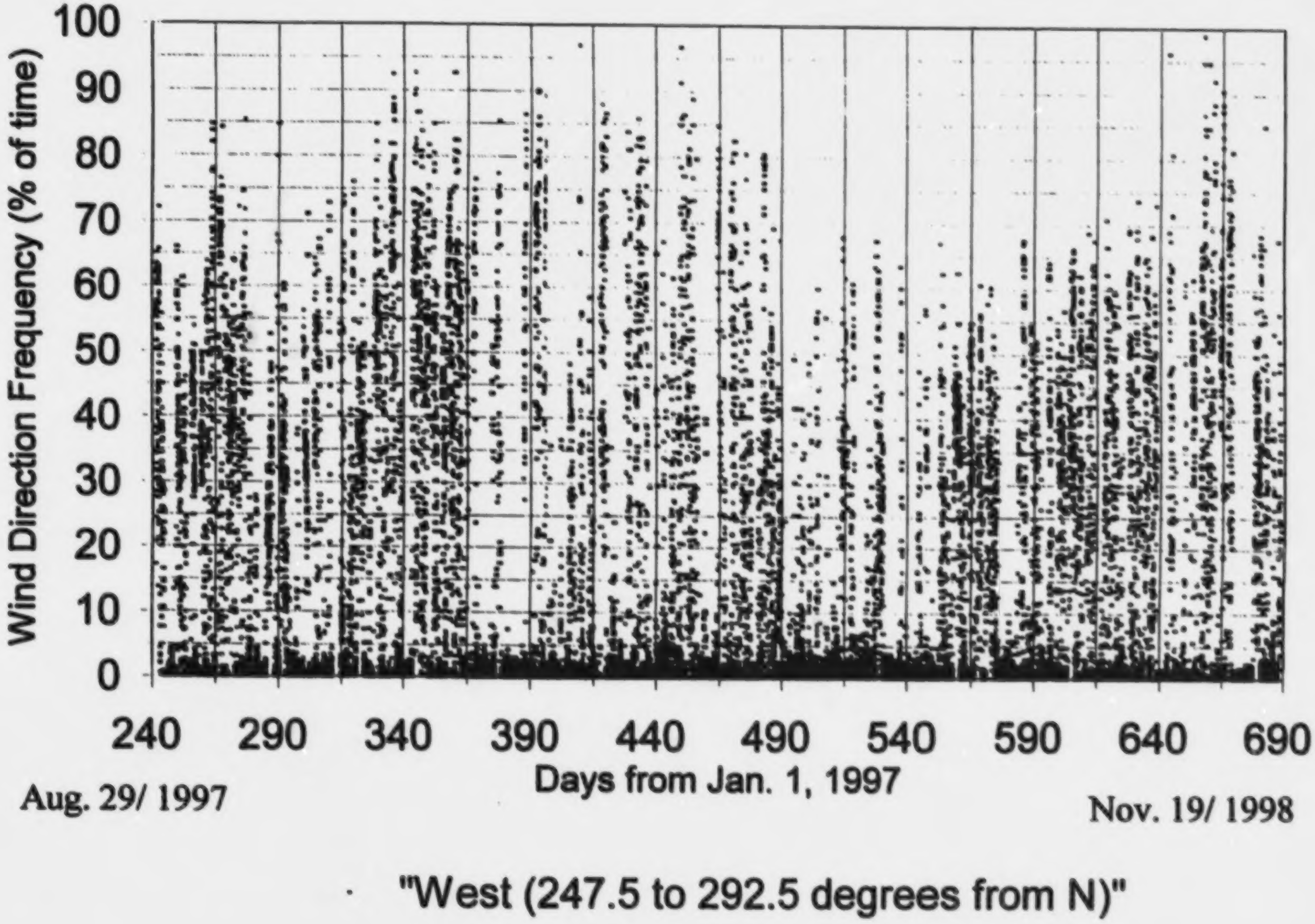
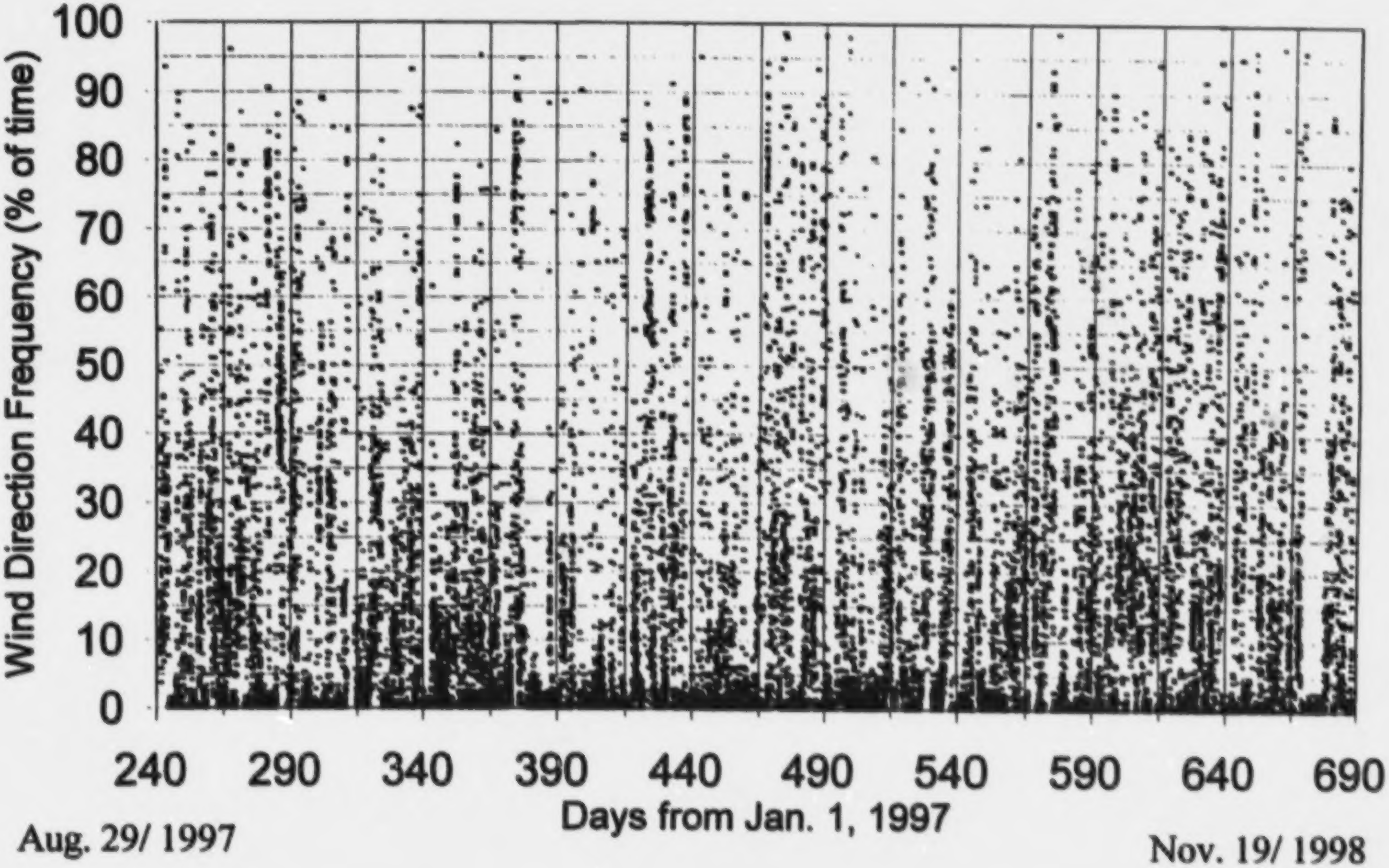


Figure 14.. Wind direction frequency for west direction.



NorthWest (292.5 to 337.5 deg. from N)

Figure 15. Wind direction frequency for northwest direction.

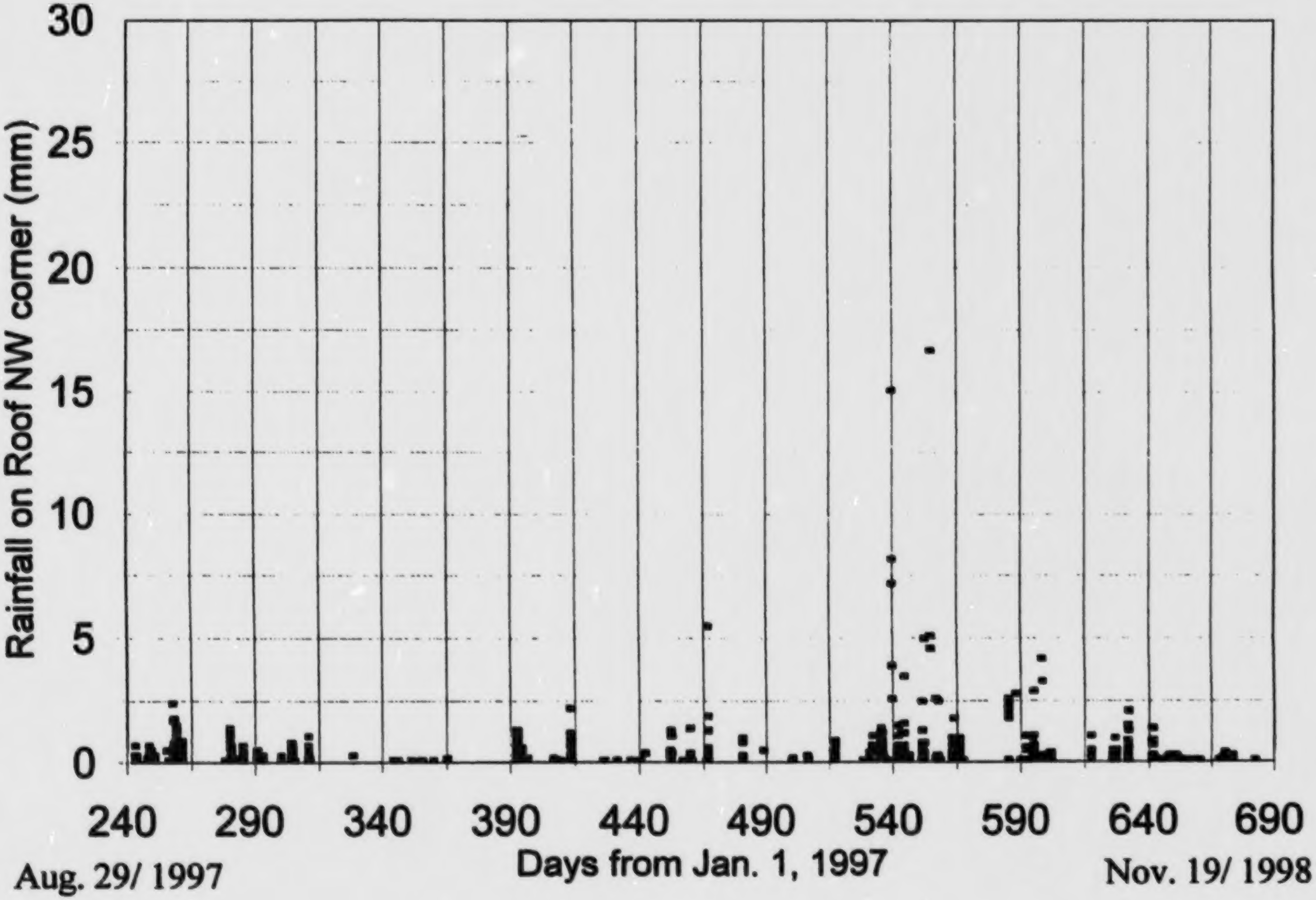


Figure 16. Precipitation on the roof at NW corner.

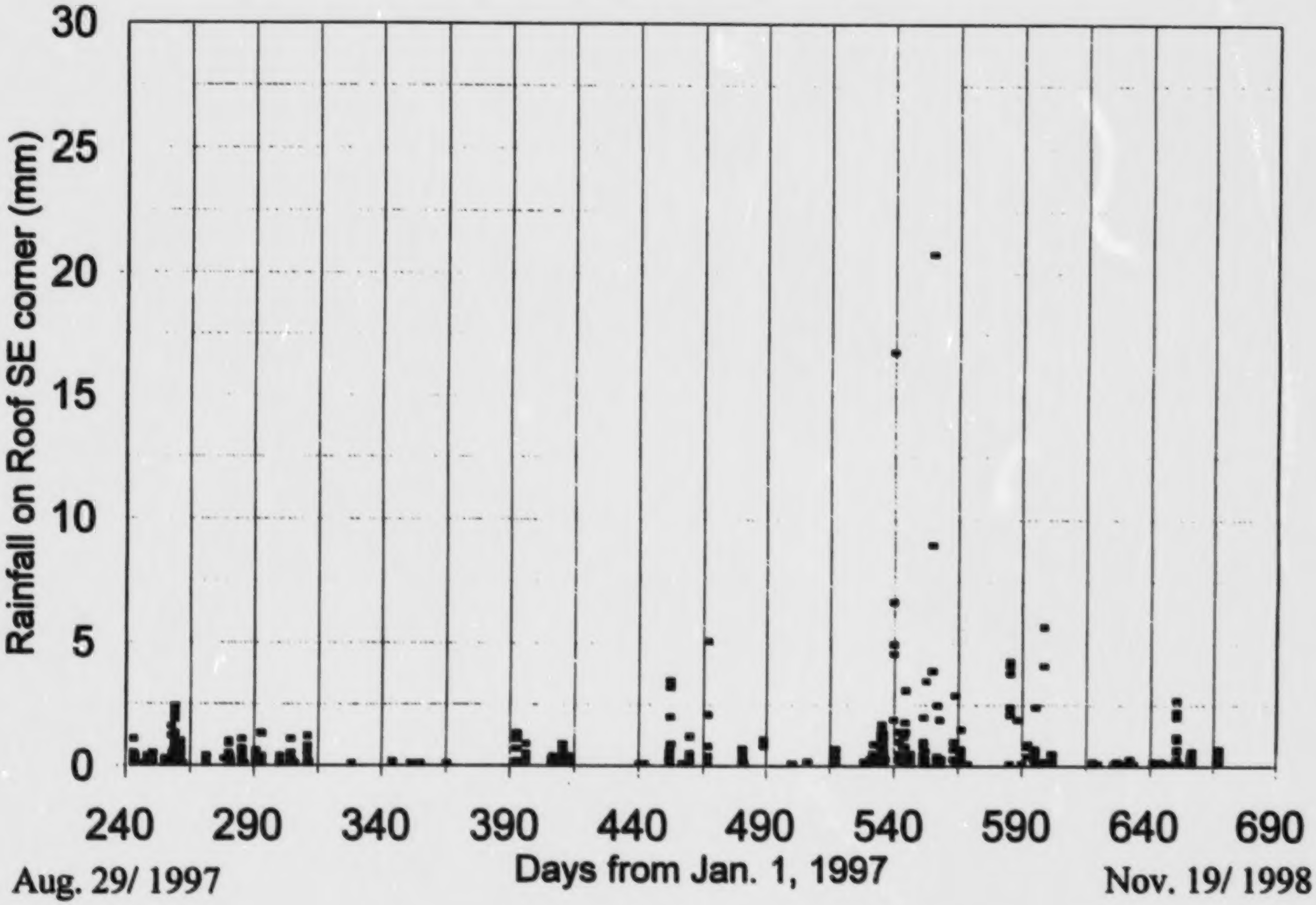
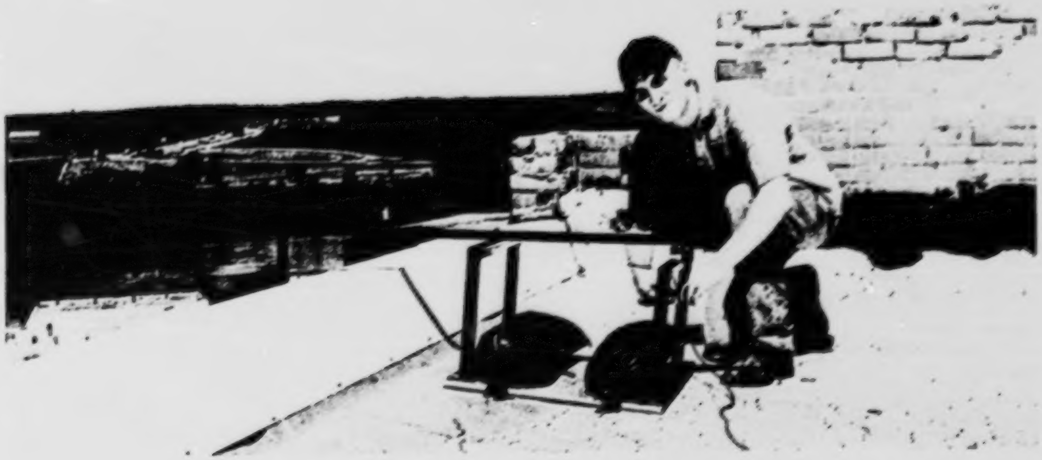


Figure 17. Precipitation on the roof at SE corner.



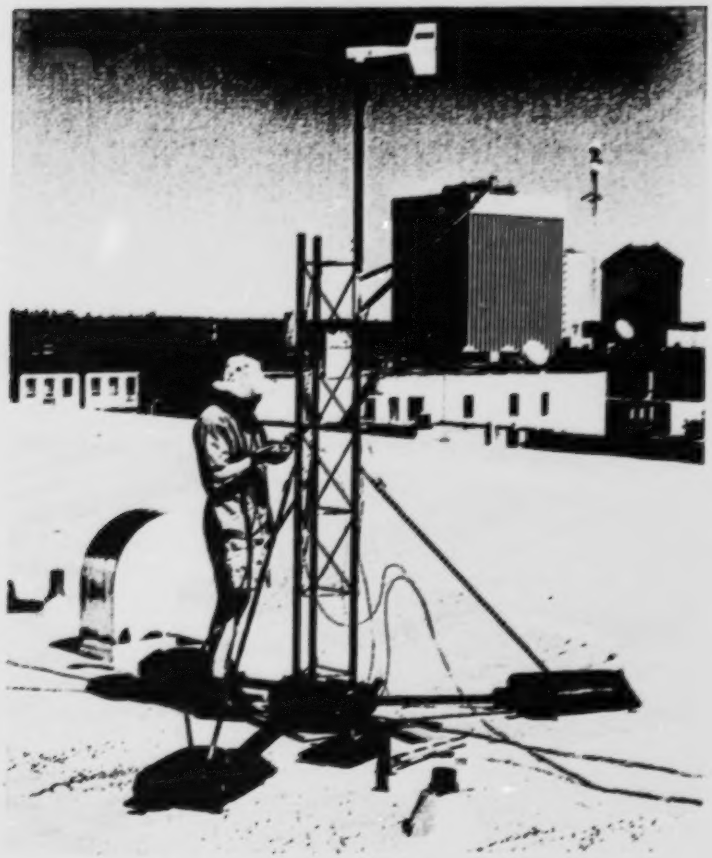


Figure 18. Installation of the rain gauge on the northwest corner of the roof. (Upper photo) Installation of the weather station on the roof of the building. (A rain gauge was located here also.) (Lower photo)

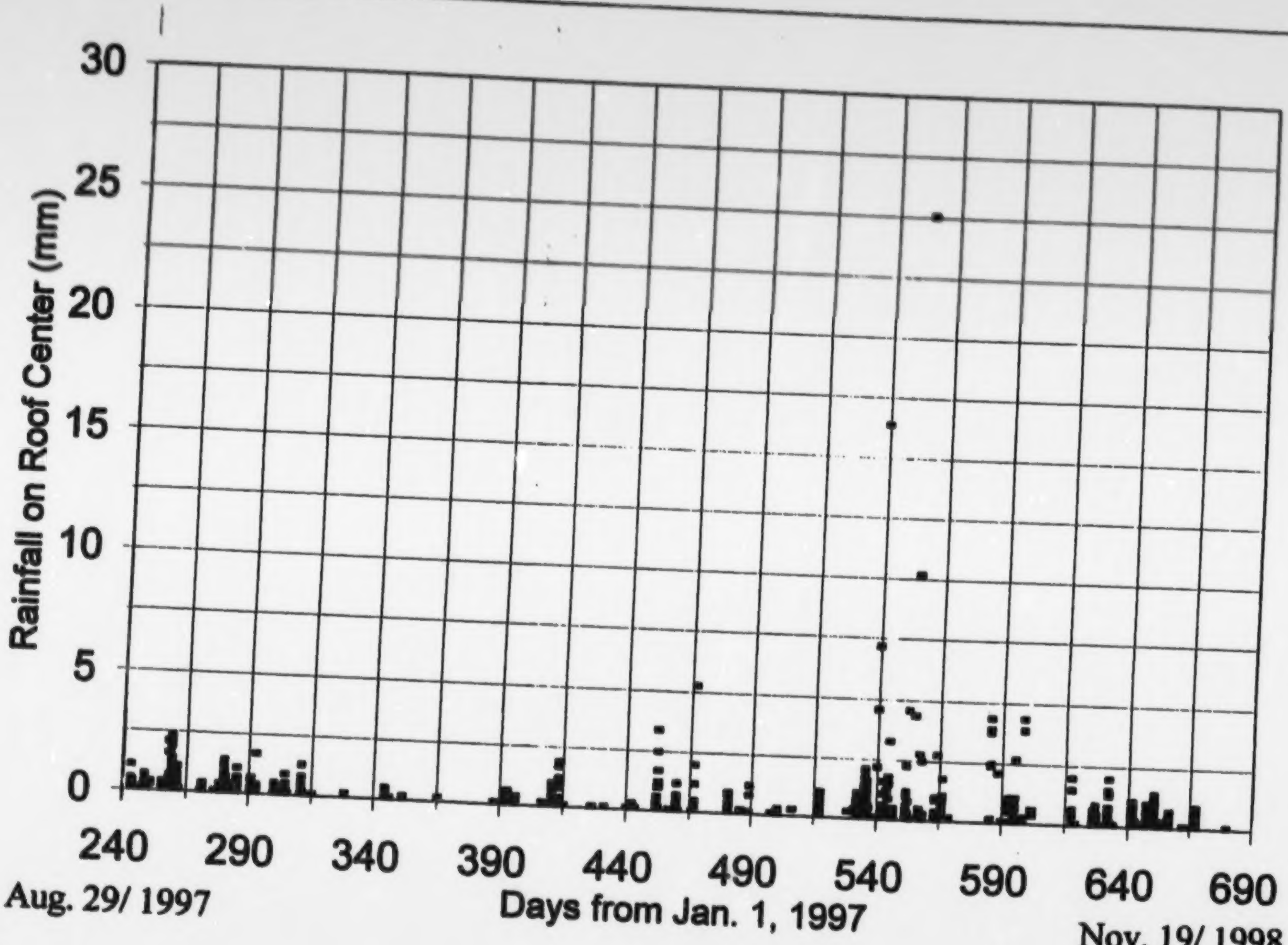


Figure 19. Precipitation on the roof at the center.

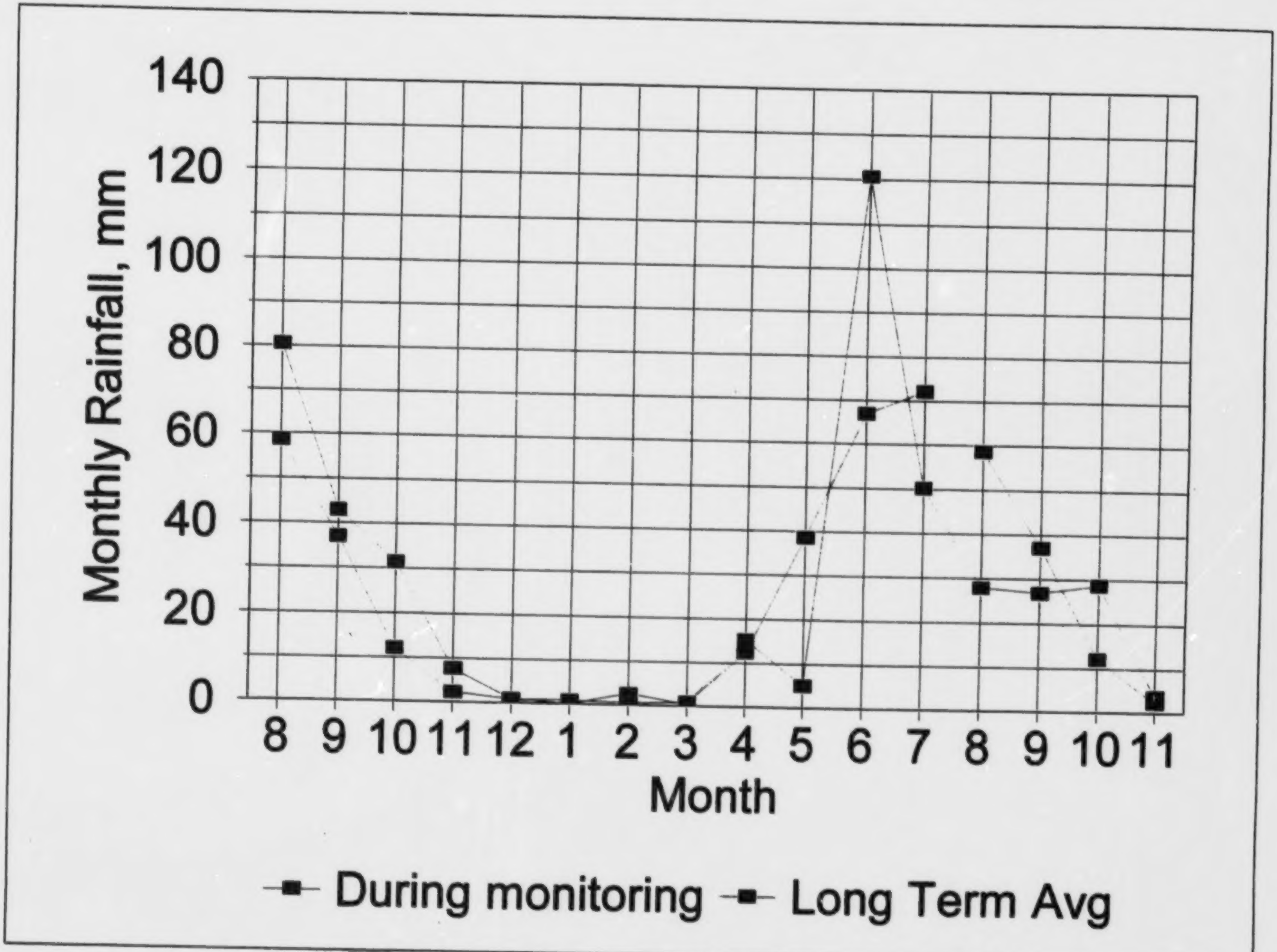


Figure 20. Comparison of monthly rainfall (excluding snow) for the monitoring period (August 97 to November 98) with the long term average values.

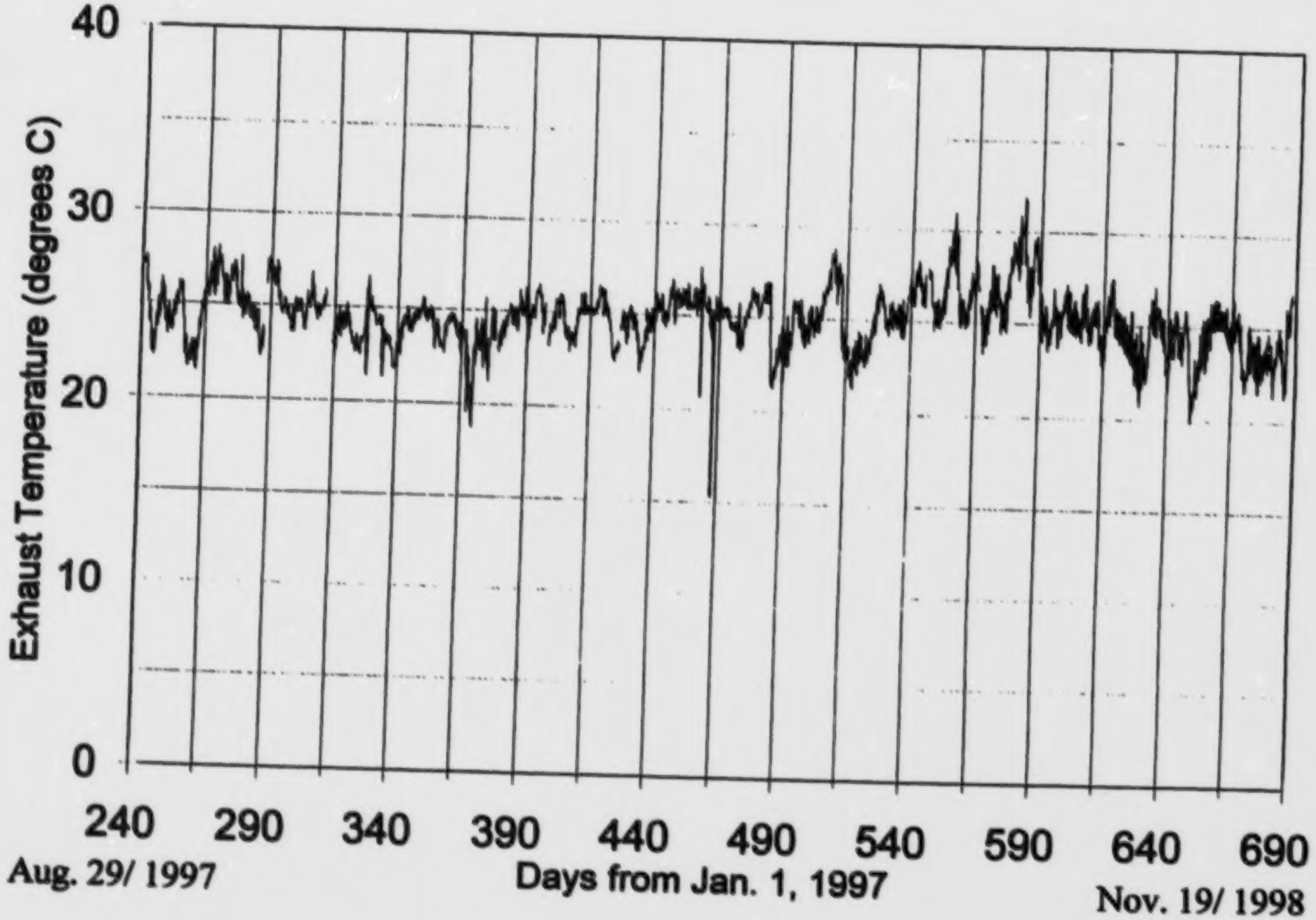


Figure 21. Temperature in the exhaust air duct on the second floor.

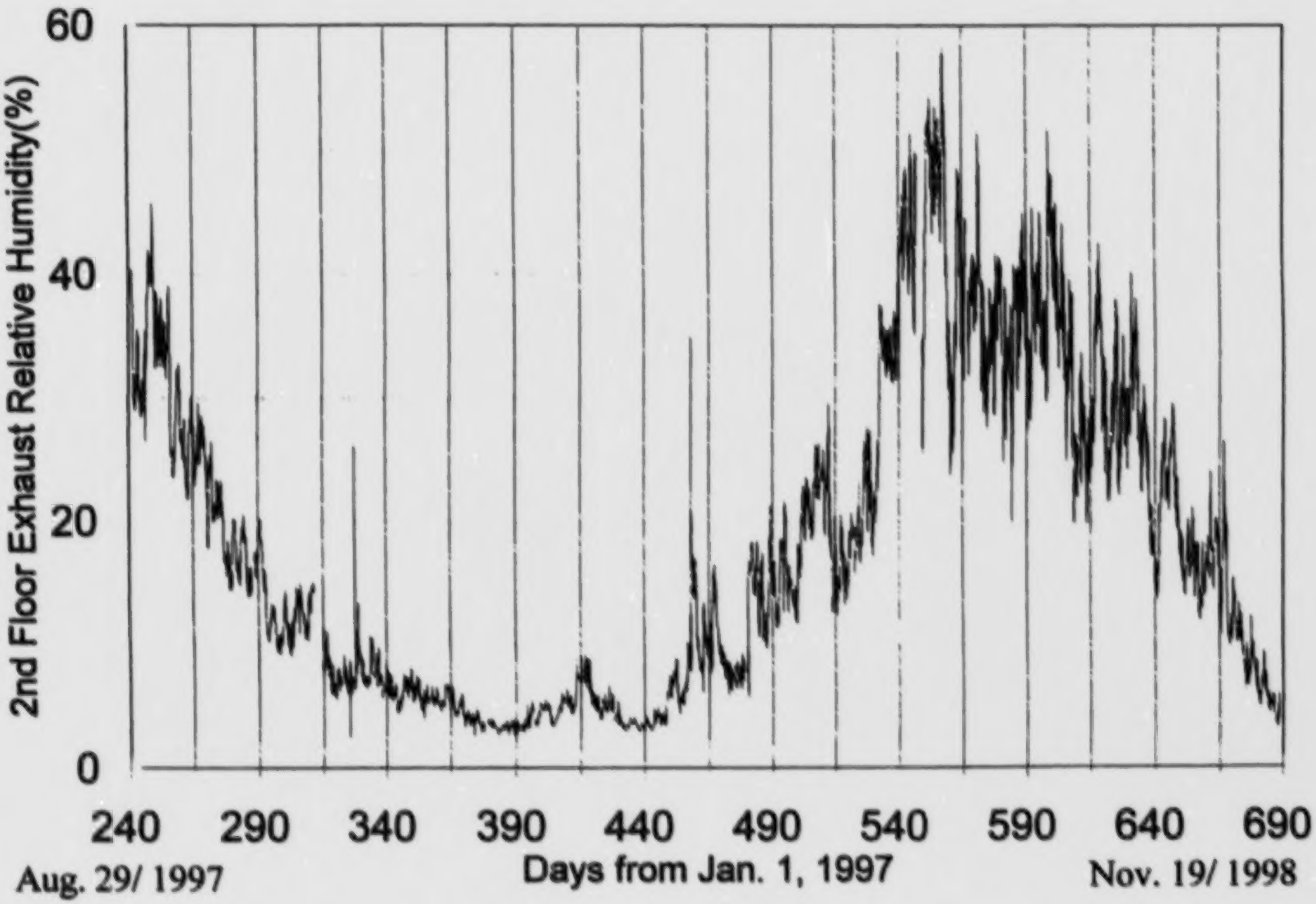


Figure 22. Relative humidity in the exhaust air duct on the second floor.

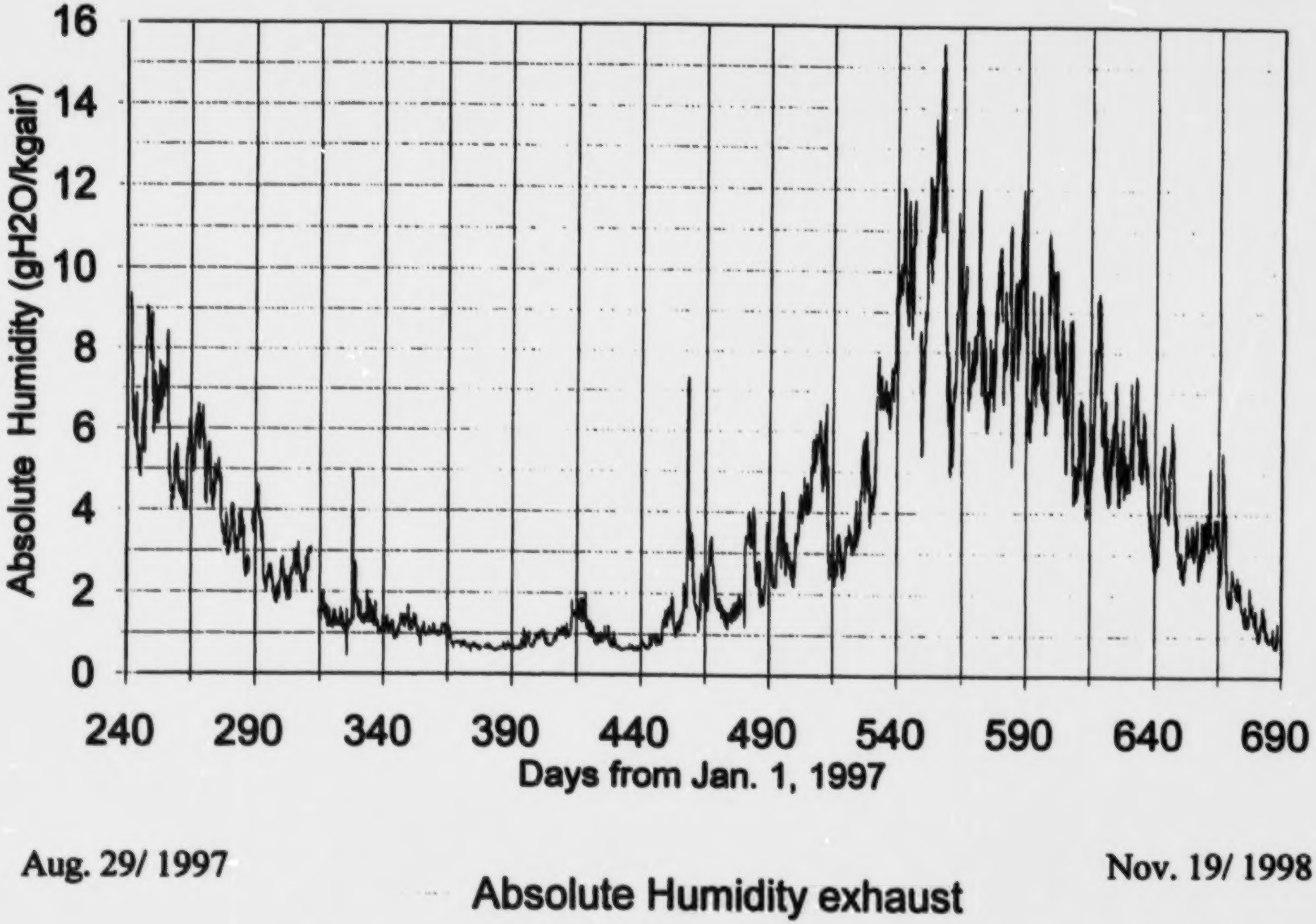


Figure 23. Absolute humidity in the exhaust air duct on the second floor.

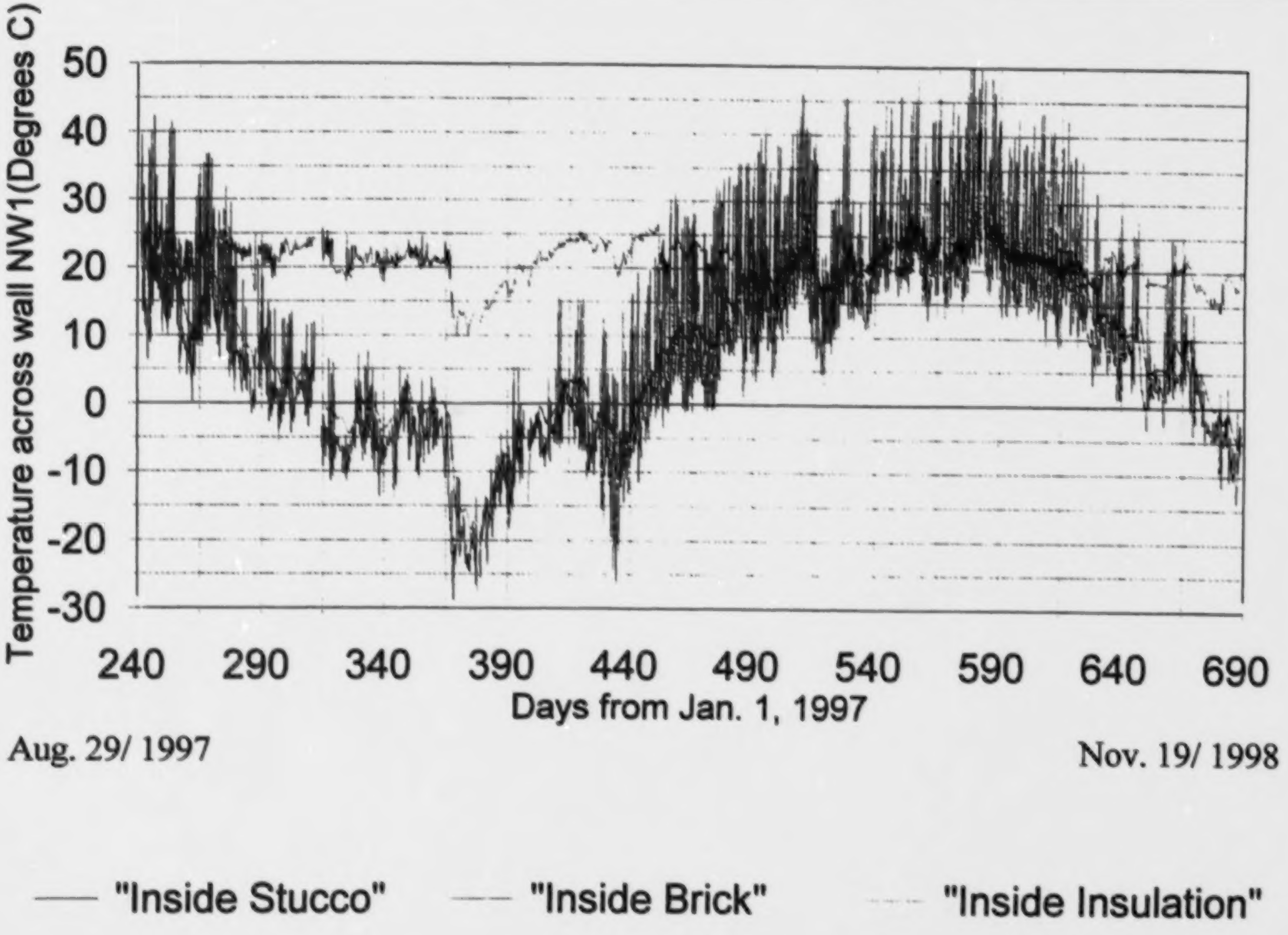


Figure 24. Temperatures at three locations in the wall section at location NW1.

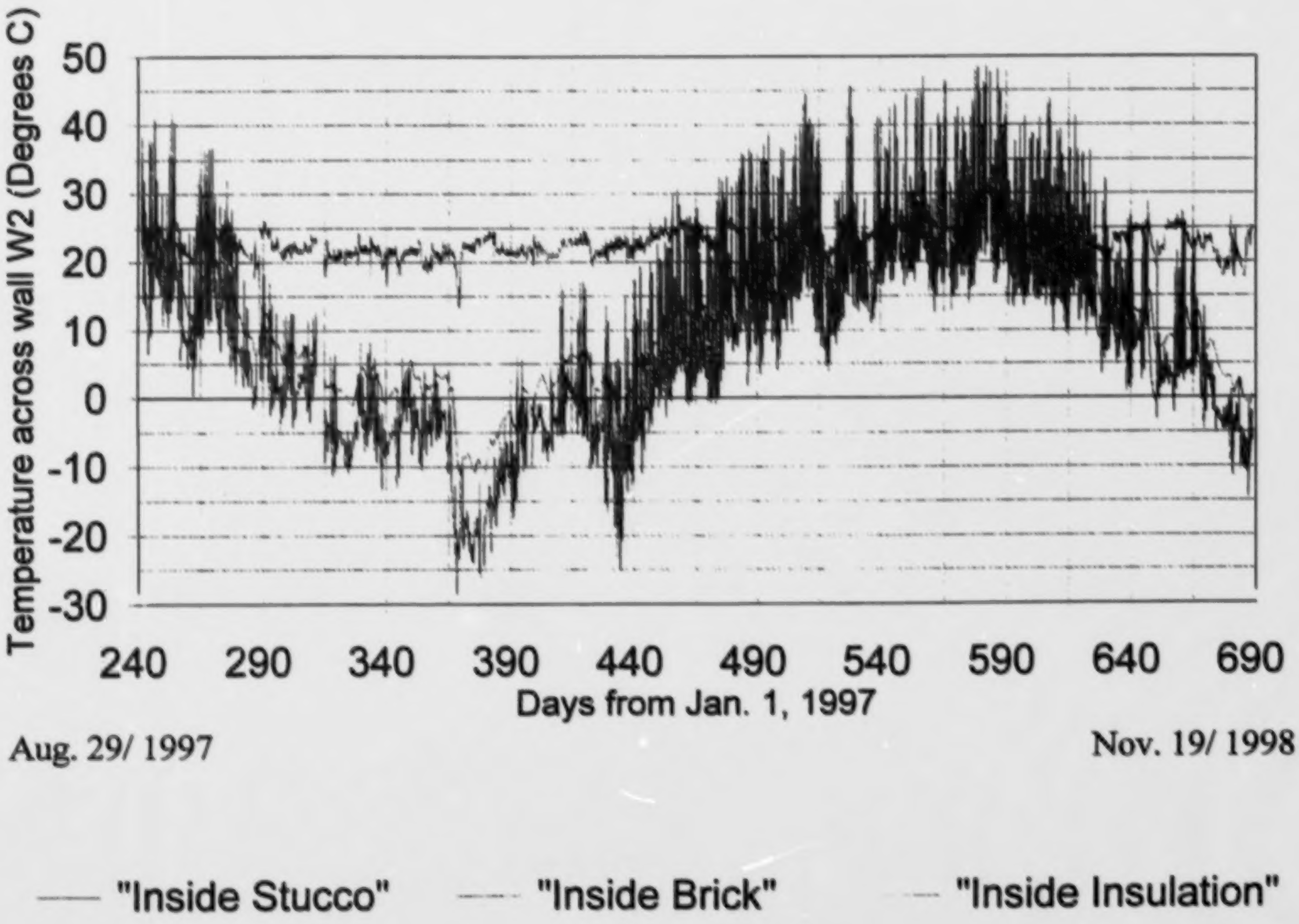


Figure 25. Temperatures at three locations in the wall section at location W2.

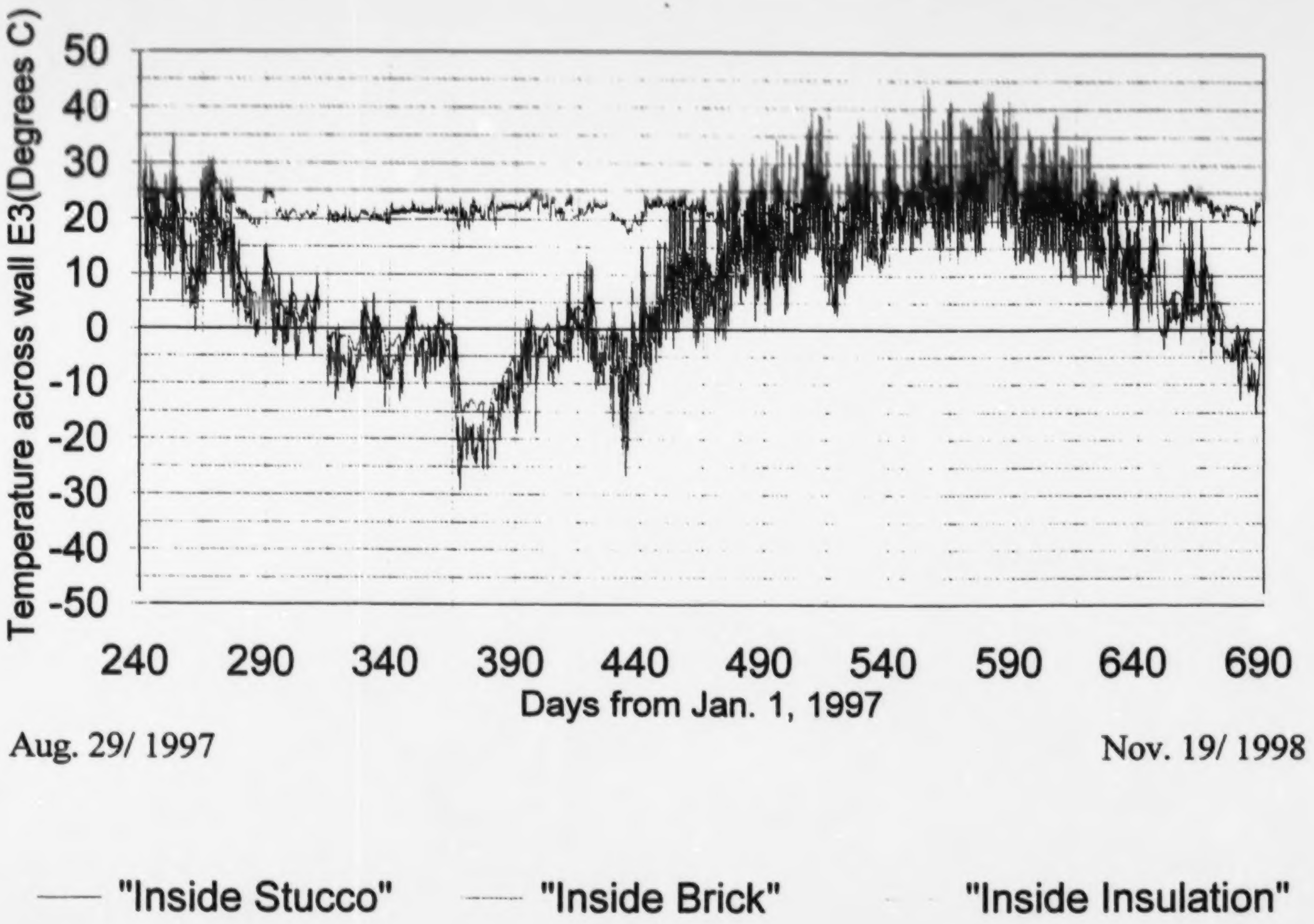


Figure 26. Temperatures at three locations in the wall section at location E3.

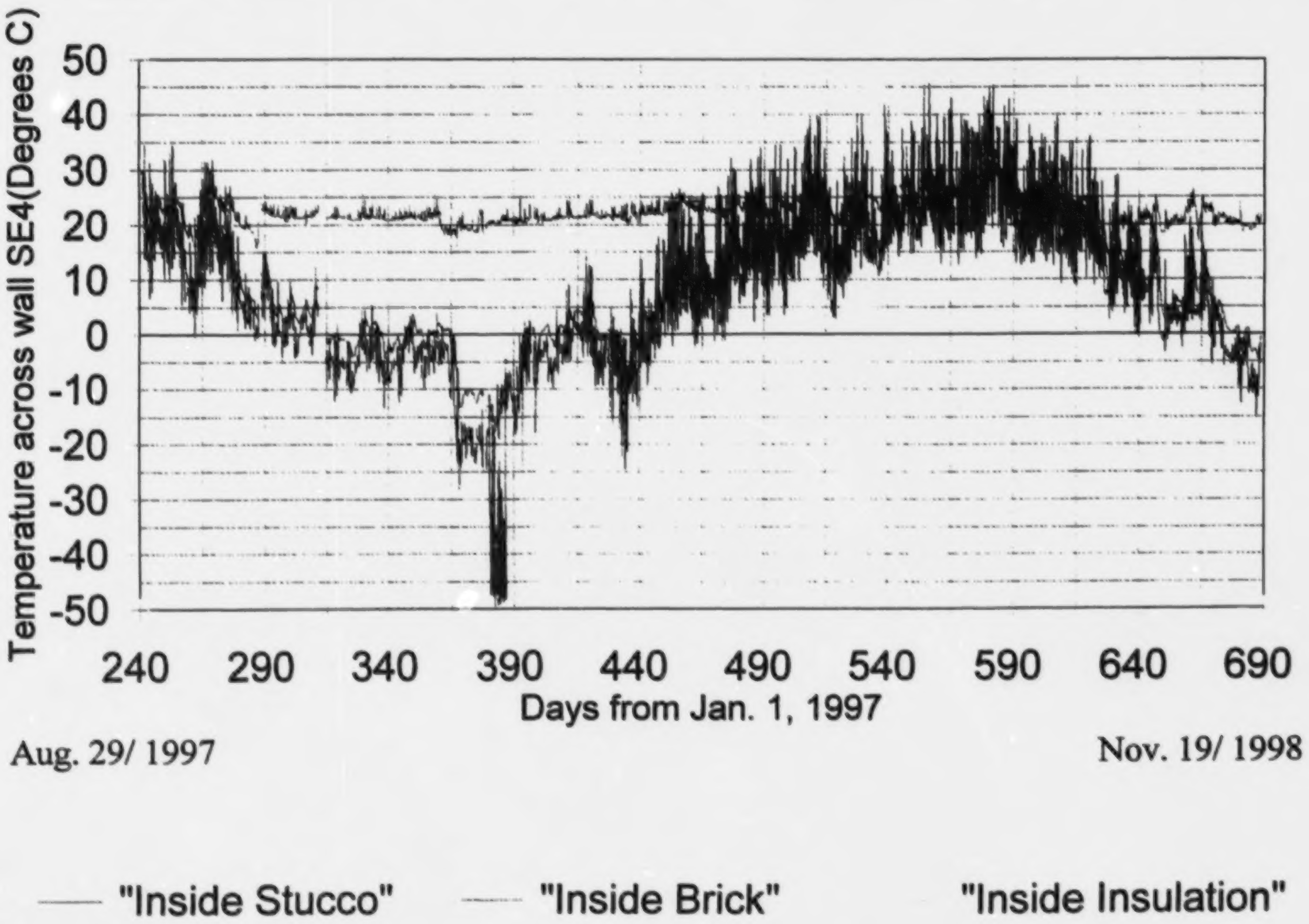


Figure 27. Temperatures at three locations in the wall section at location SE4.

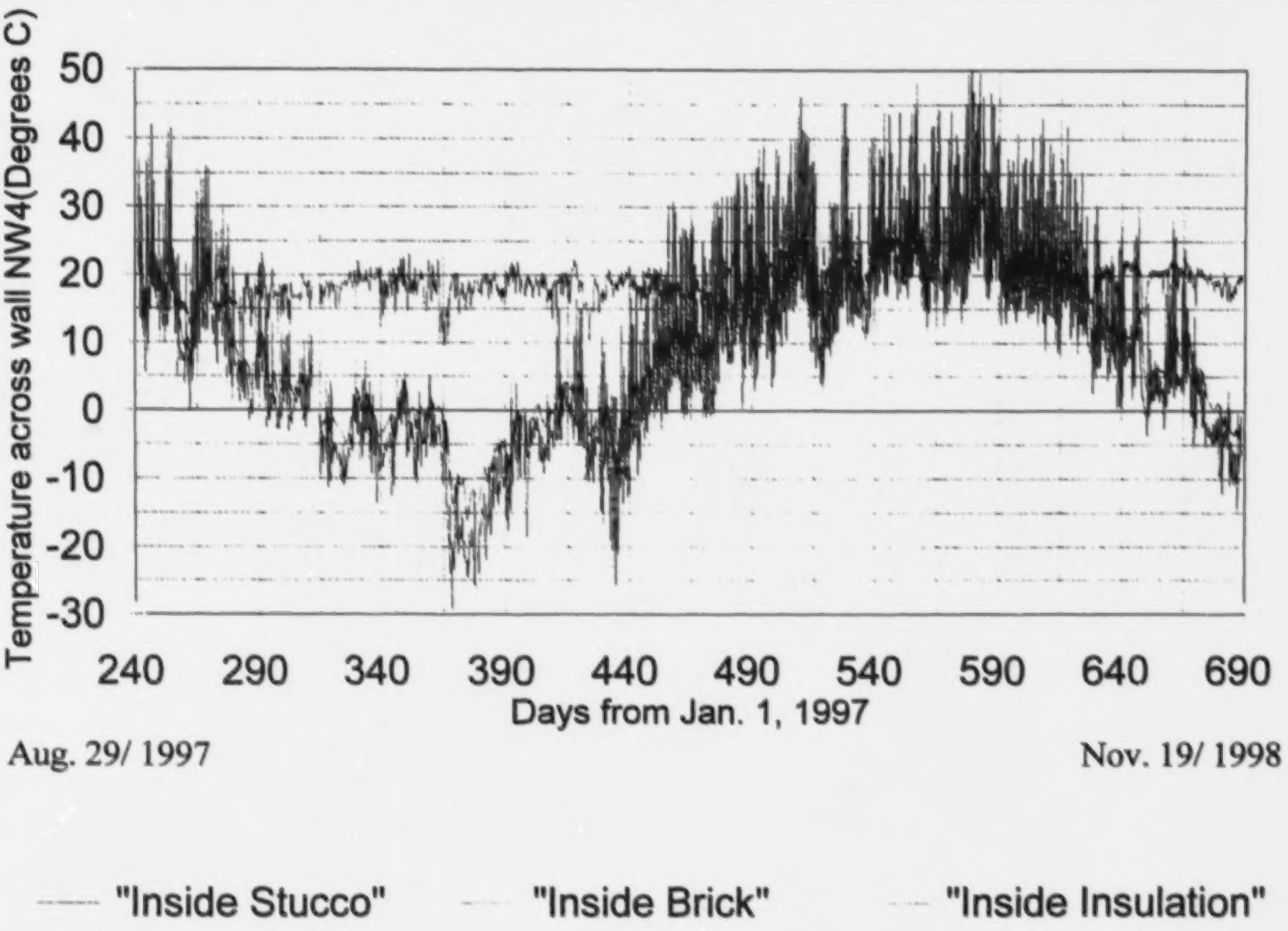


Figure 28. Temperatures at three locations in the wall section at location NW4.

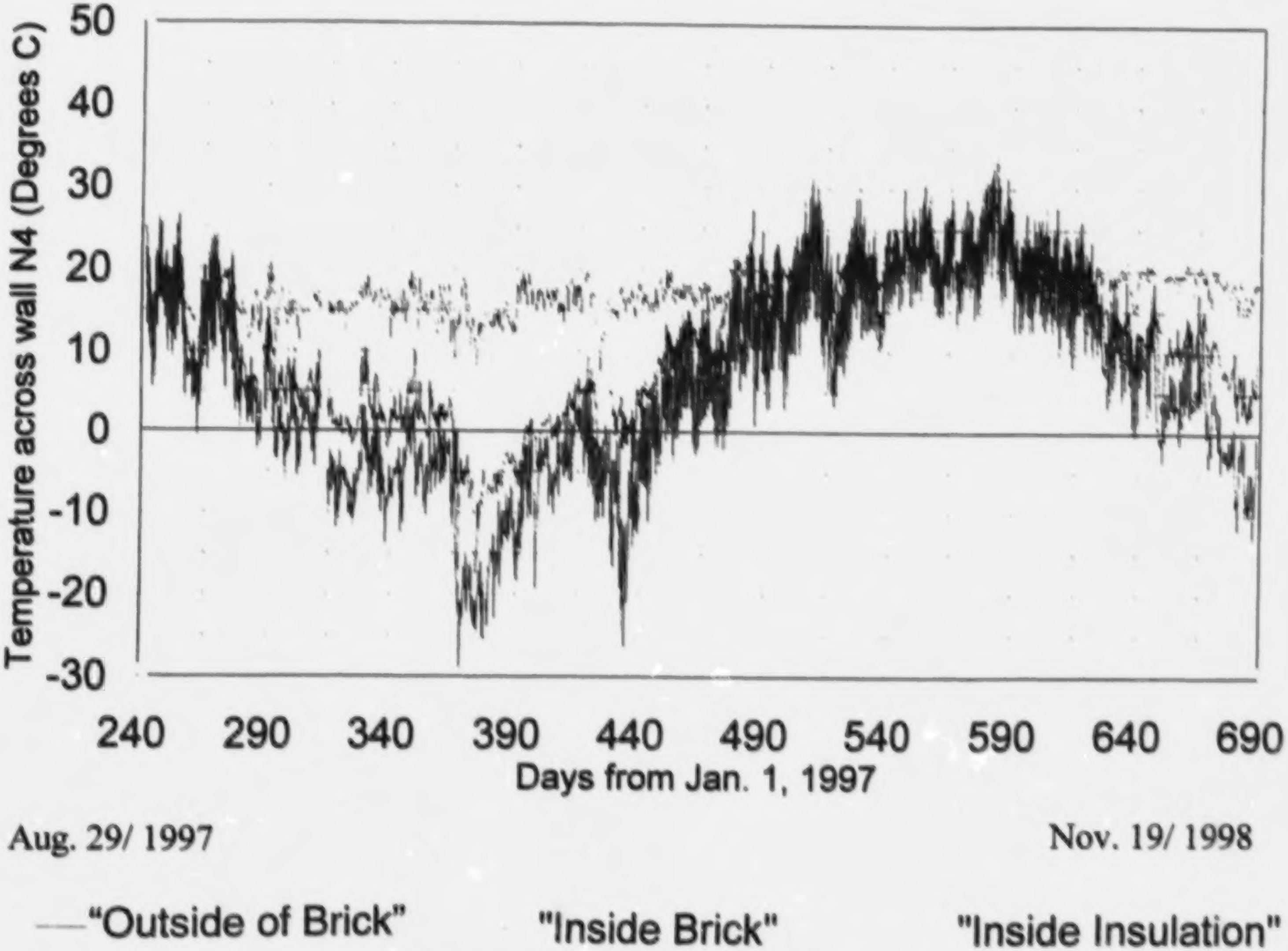


Figure 29. Temperatures at three locations in the wall section at location N4.

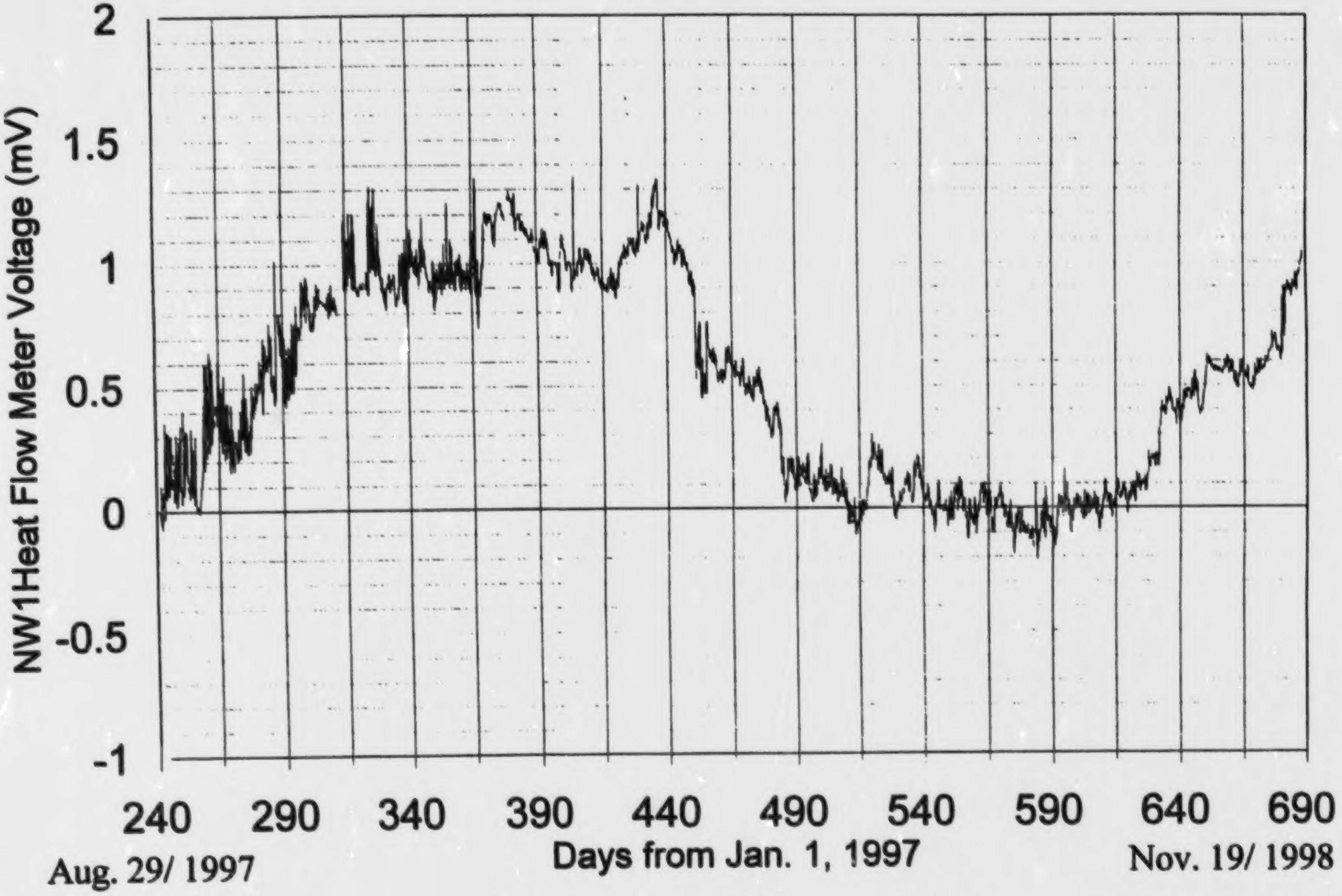


Figure 30. Heat flow meter voltage output at location NW1.

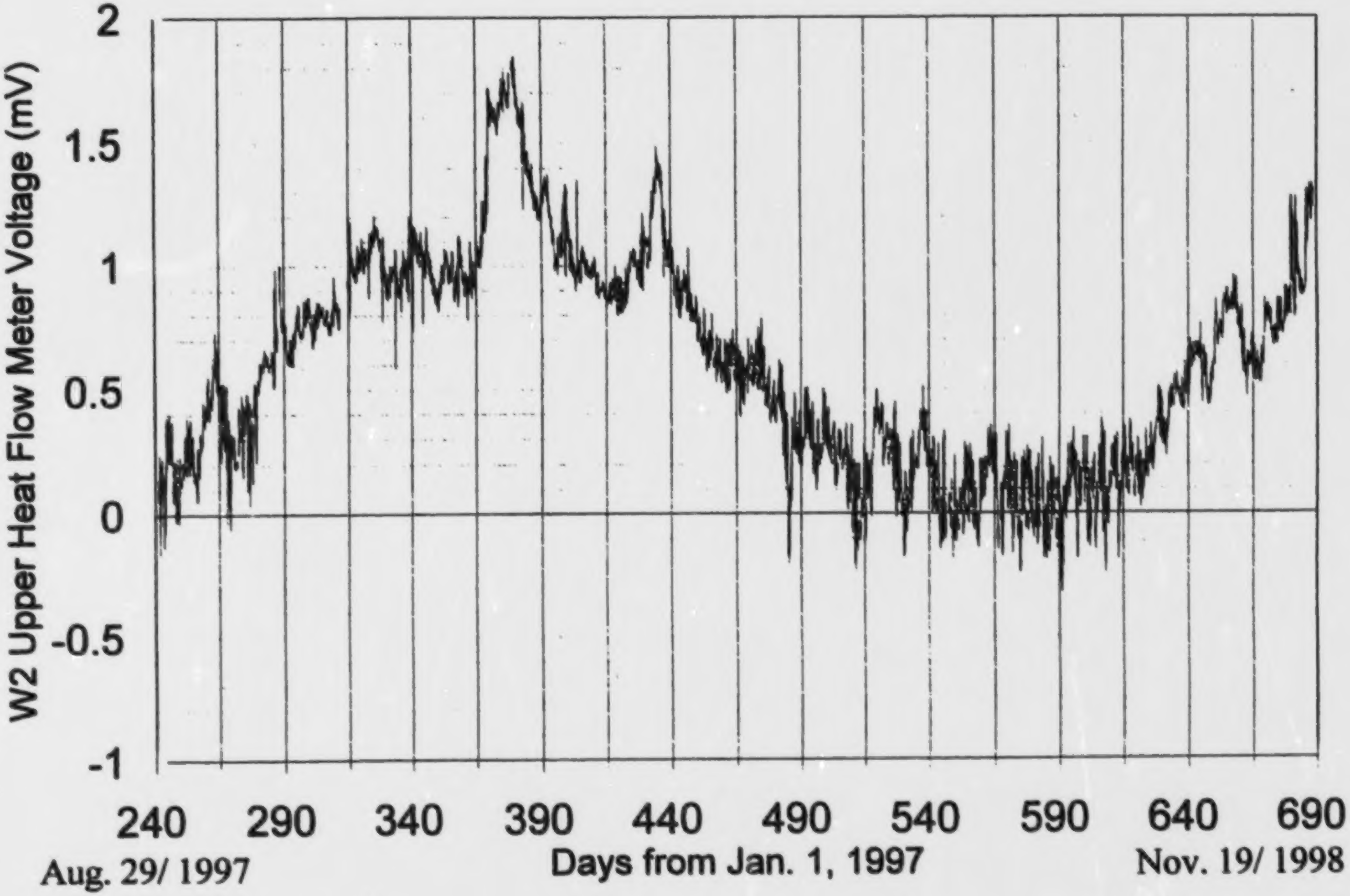


Figure 31 Heat flow meter voltage output at location W2 (Upper).

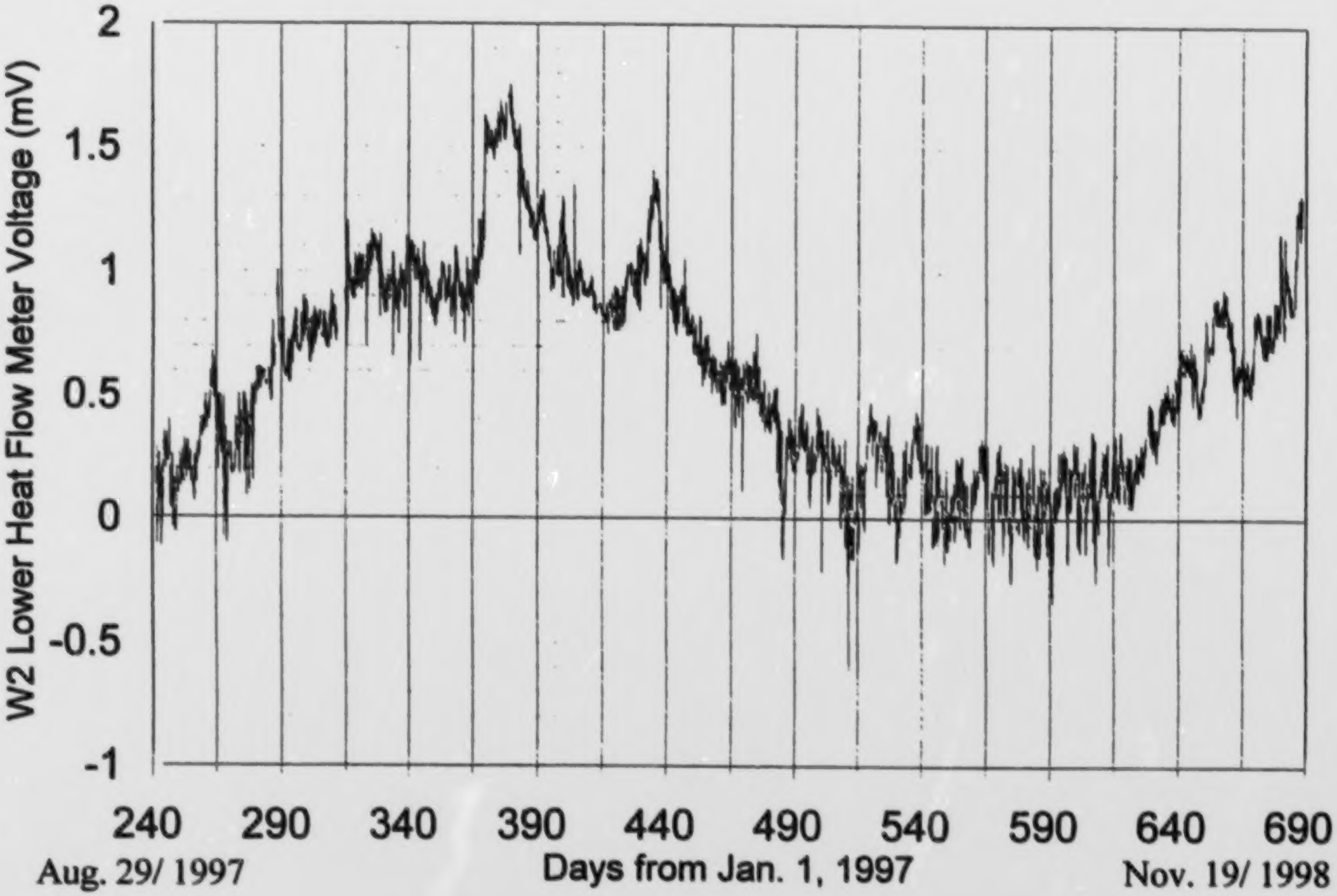


Figure 32. Heat flow meter voltage output at location W2 (Lower).

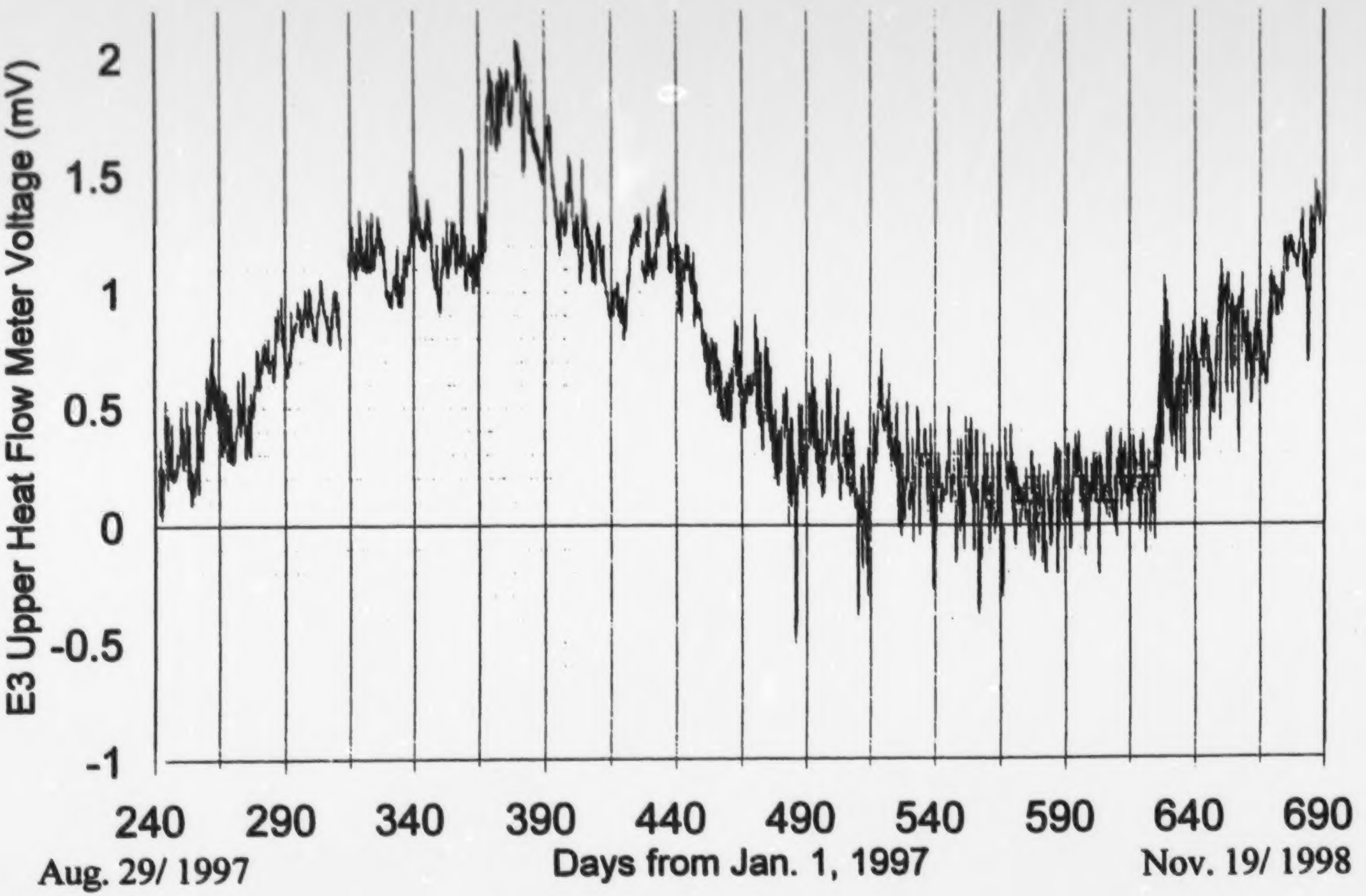


Figure 33. Heat flow meter voltage output at location E3 (Upper).

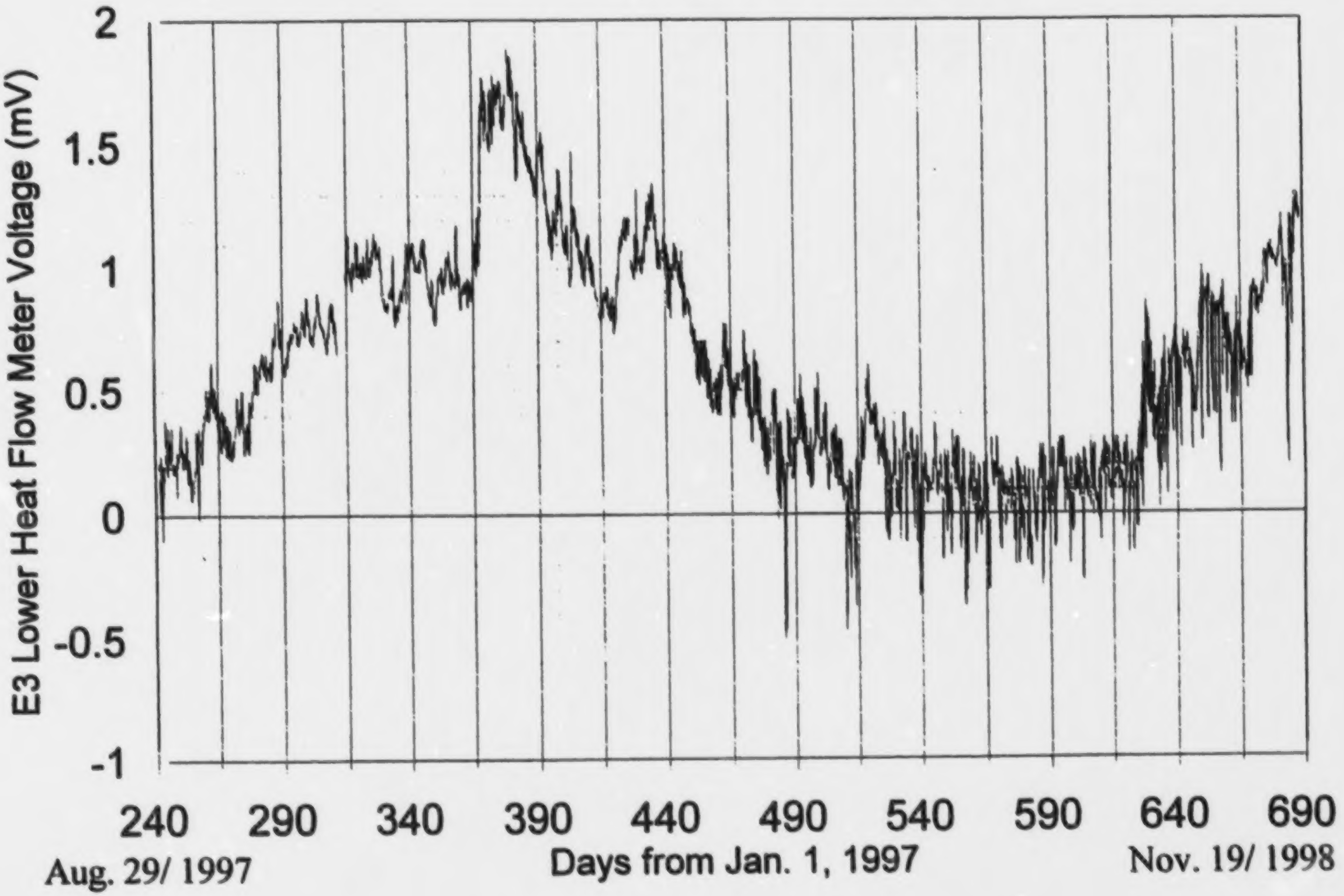


Figure 34. Heat flow meter voltage output at location E3 (Lower).

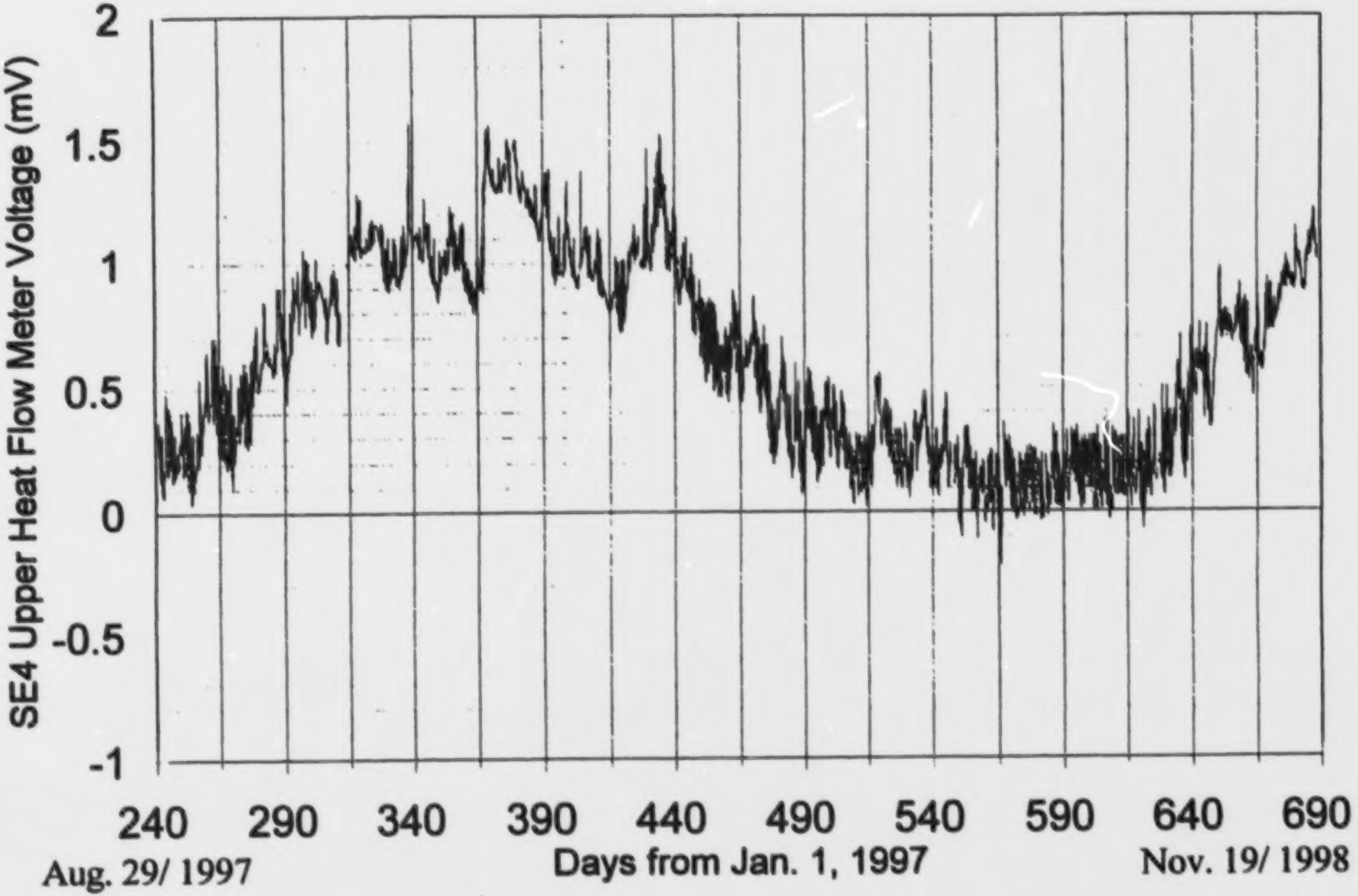


Figure 35. Heat flow meter voltage output at location SE4 (Upper).

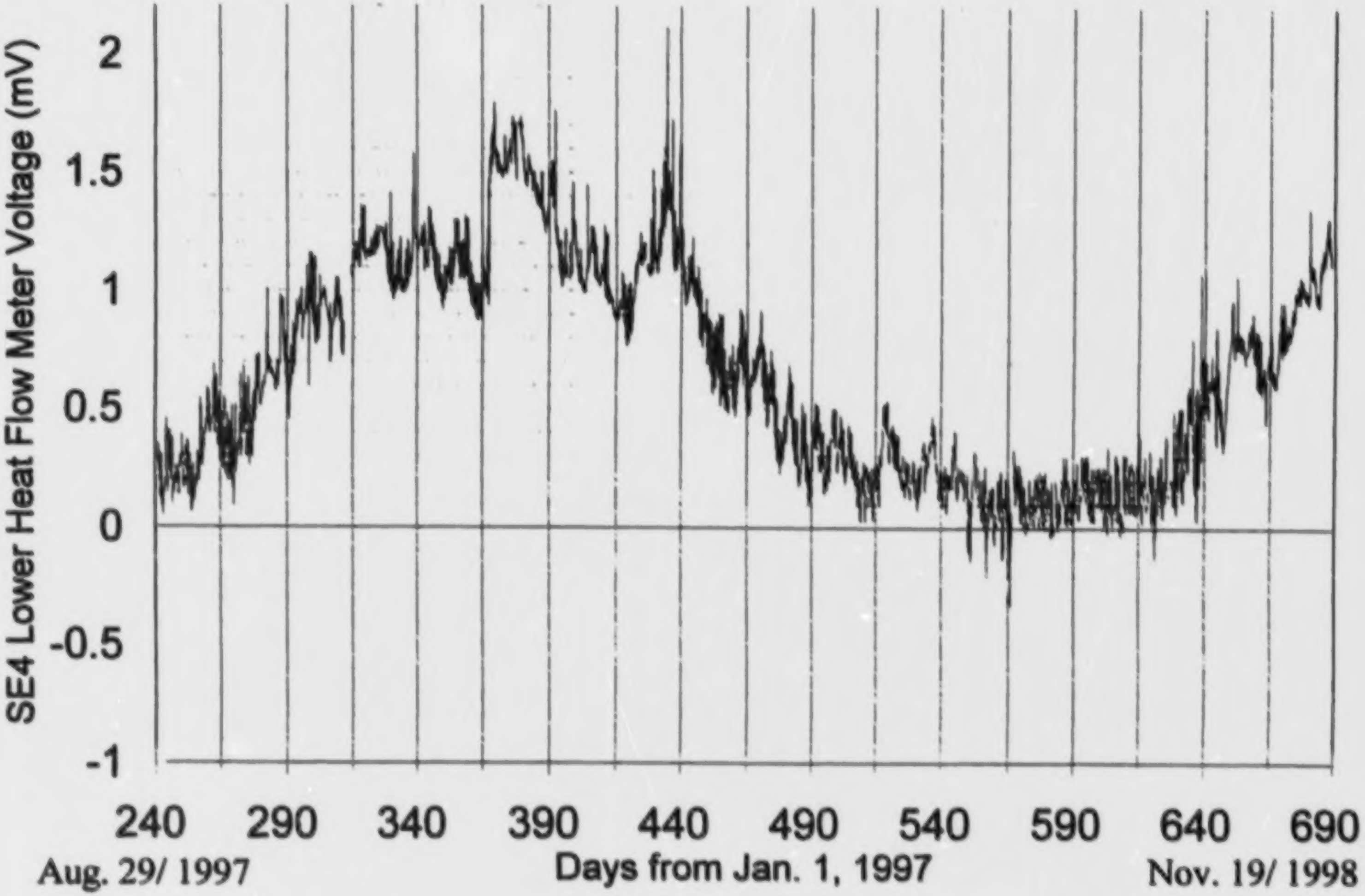


Figure 36. Heat flow meter voltage output at location SE4 (Lower).

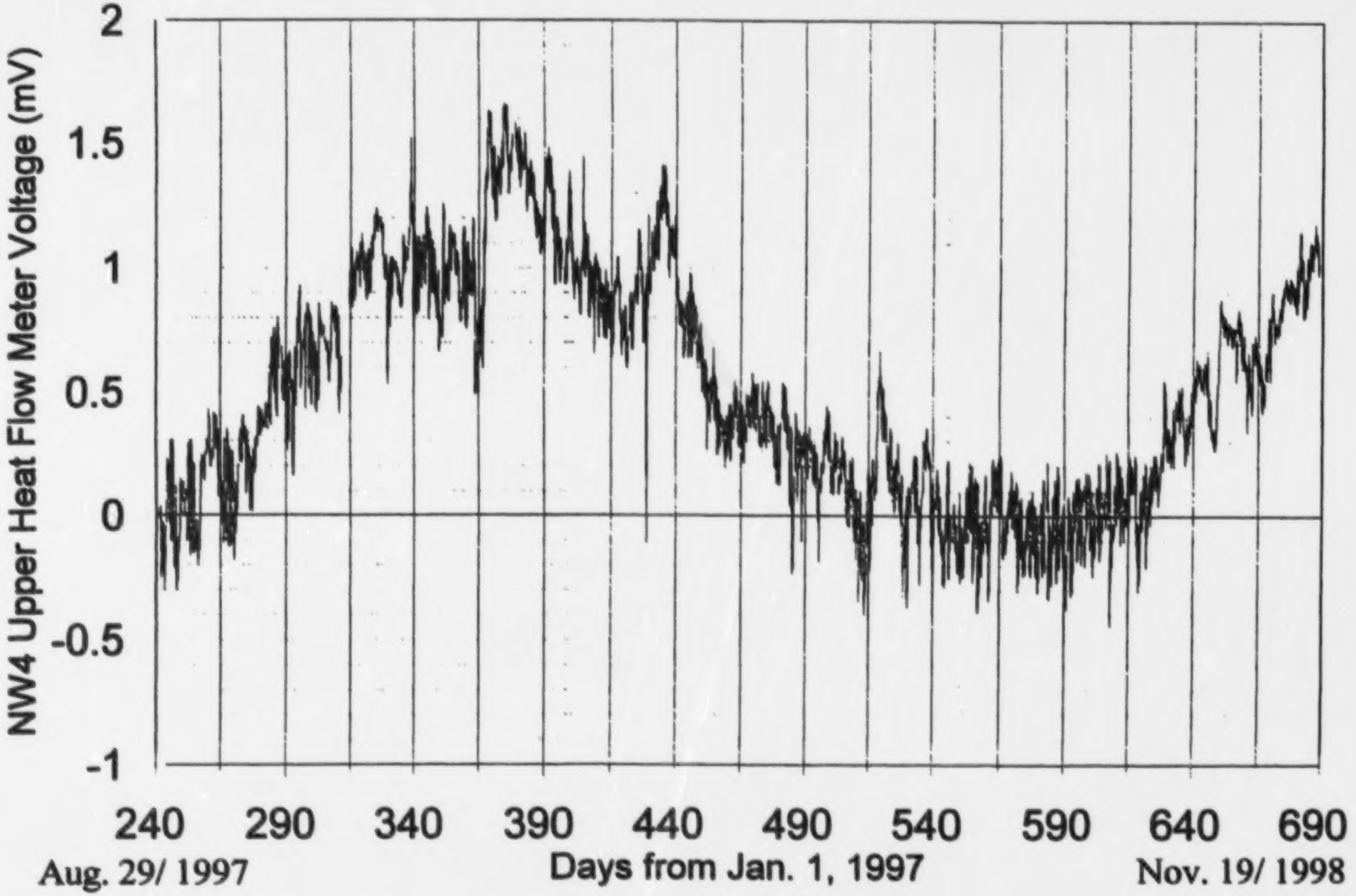


Figure 37. Heat flow meter voltage output at location NW4 (Upper).

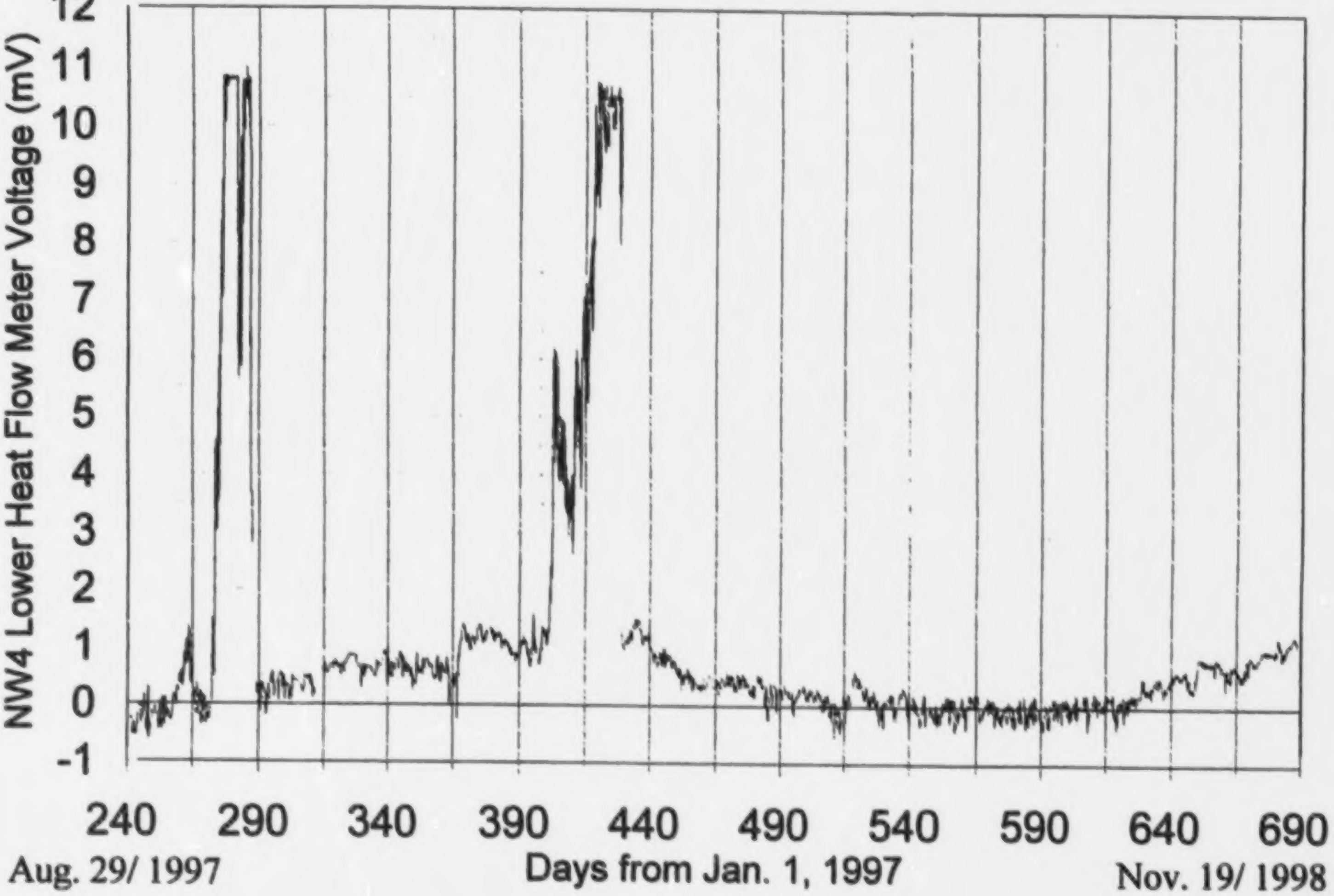


Figure 38. Heat flow meter voltage output at location NW4 (Lower).

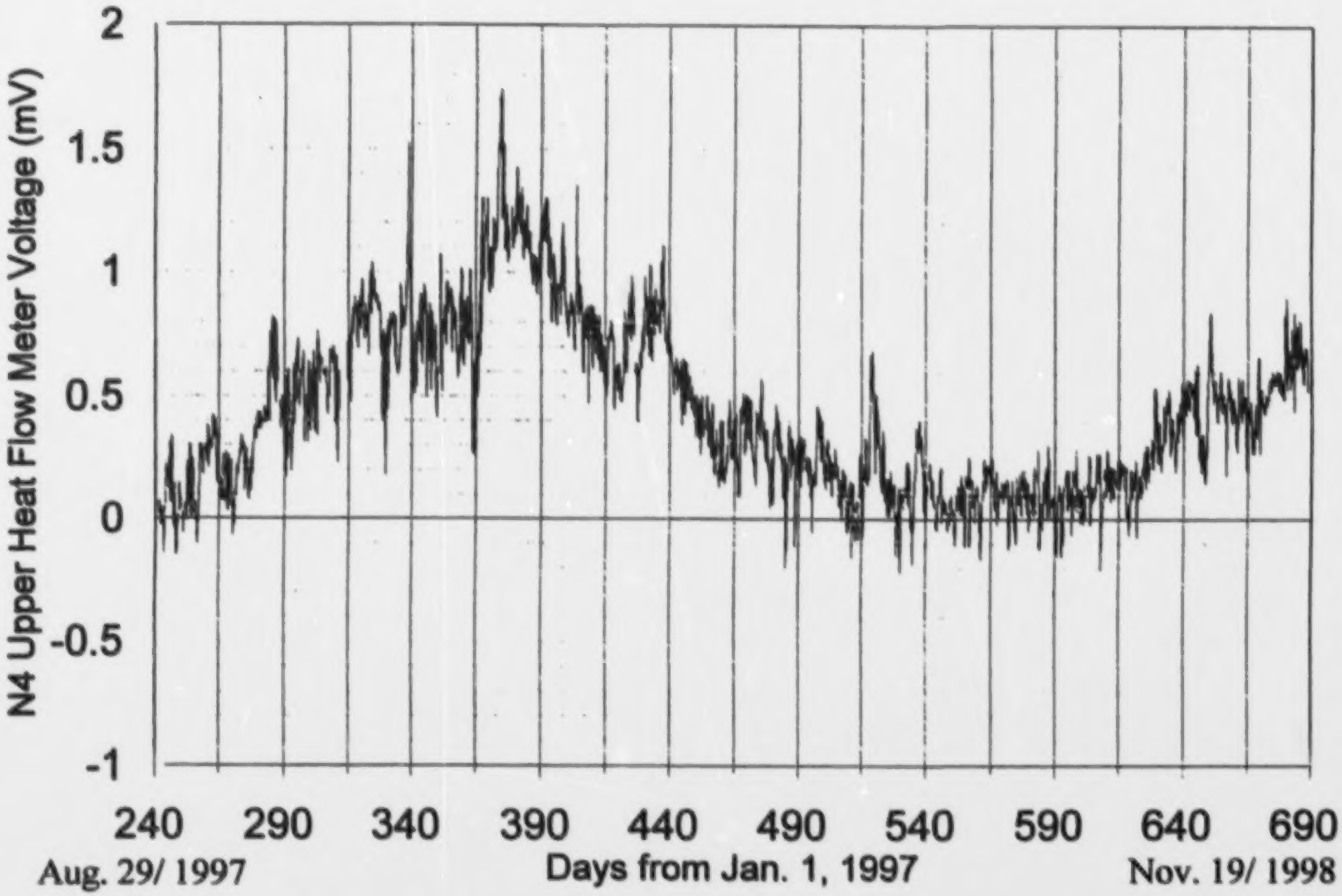


Figure 39. Heat flow meter voltage output at location N4 (Upper).

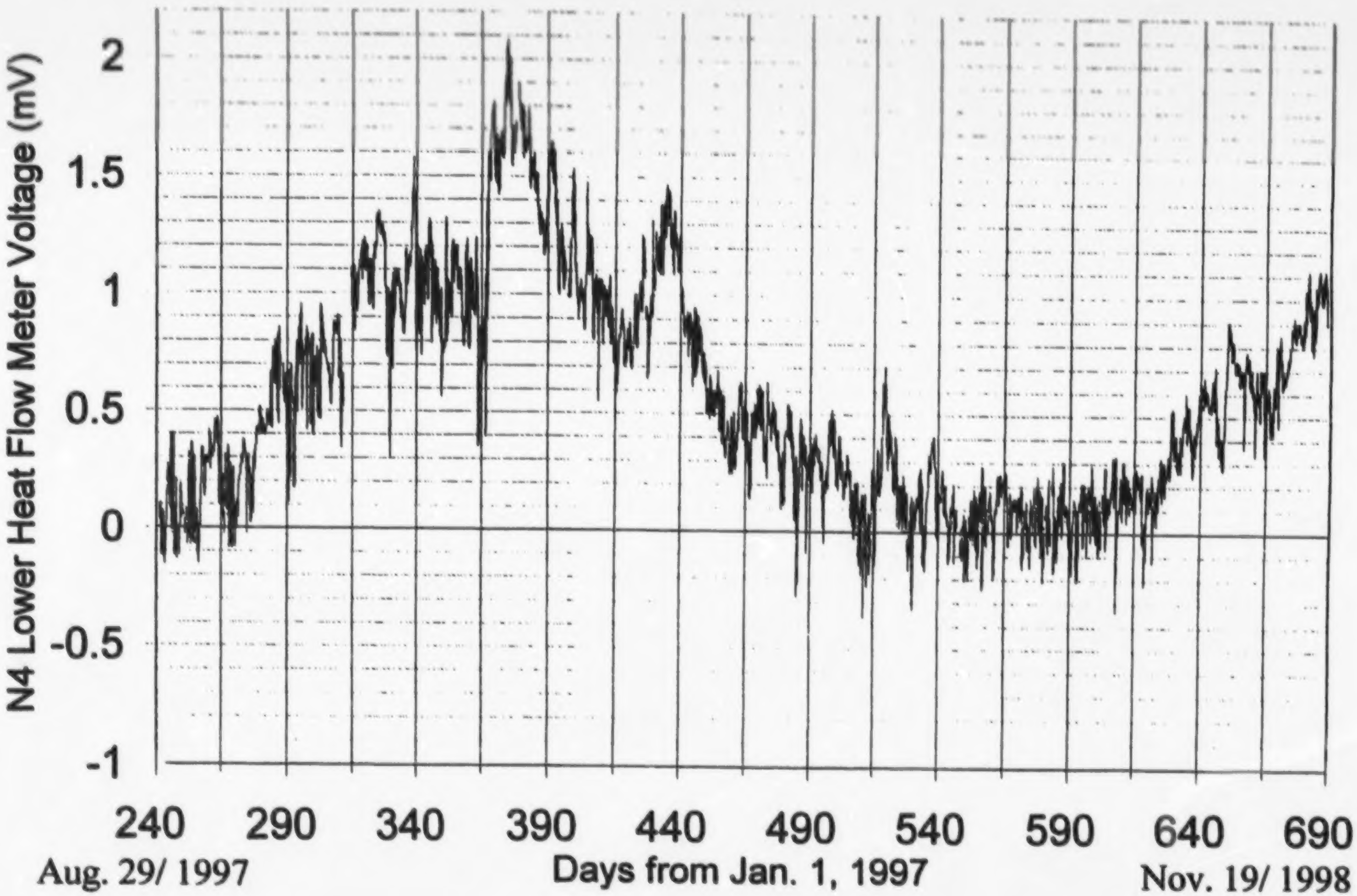


Figure 40. Heat flow meter voltage output at location N4 (Lower).

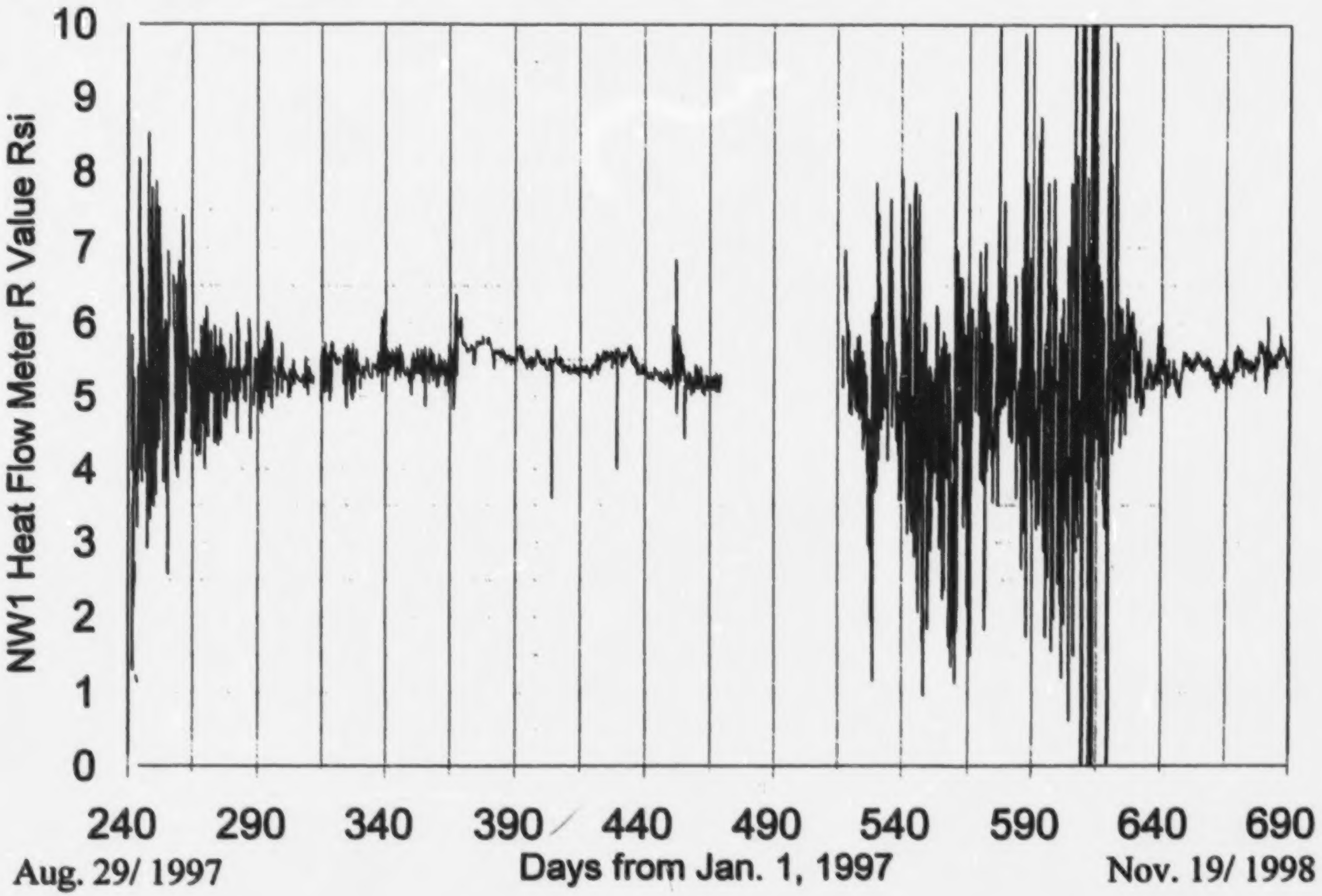


Figure 41. Calculated Insulation RSI value at location NW1.

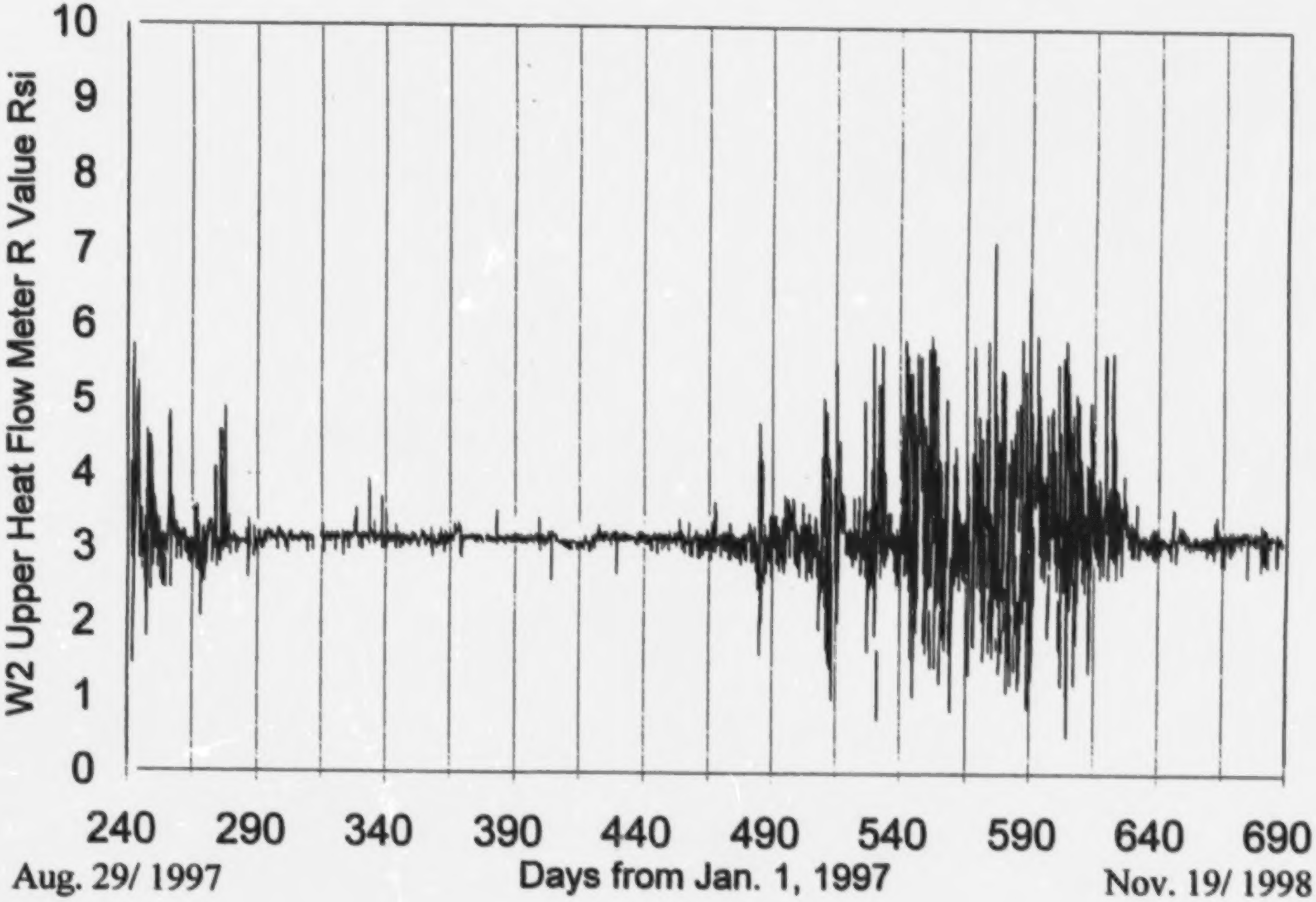


Figure 42. Calculated Insulation RSI value at location W2 (Upper).

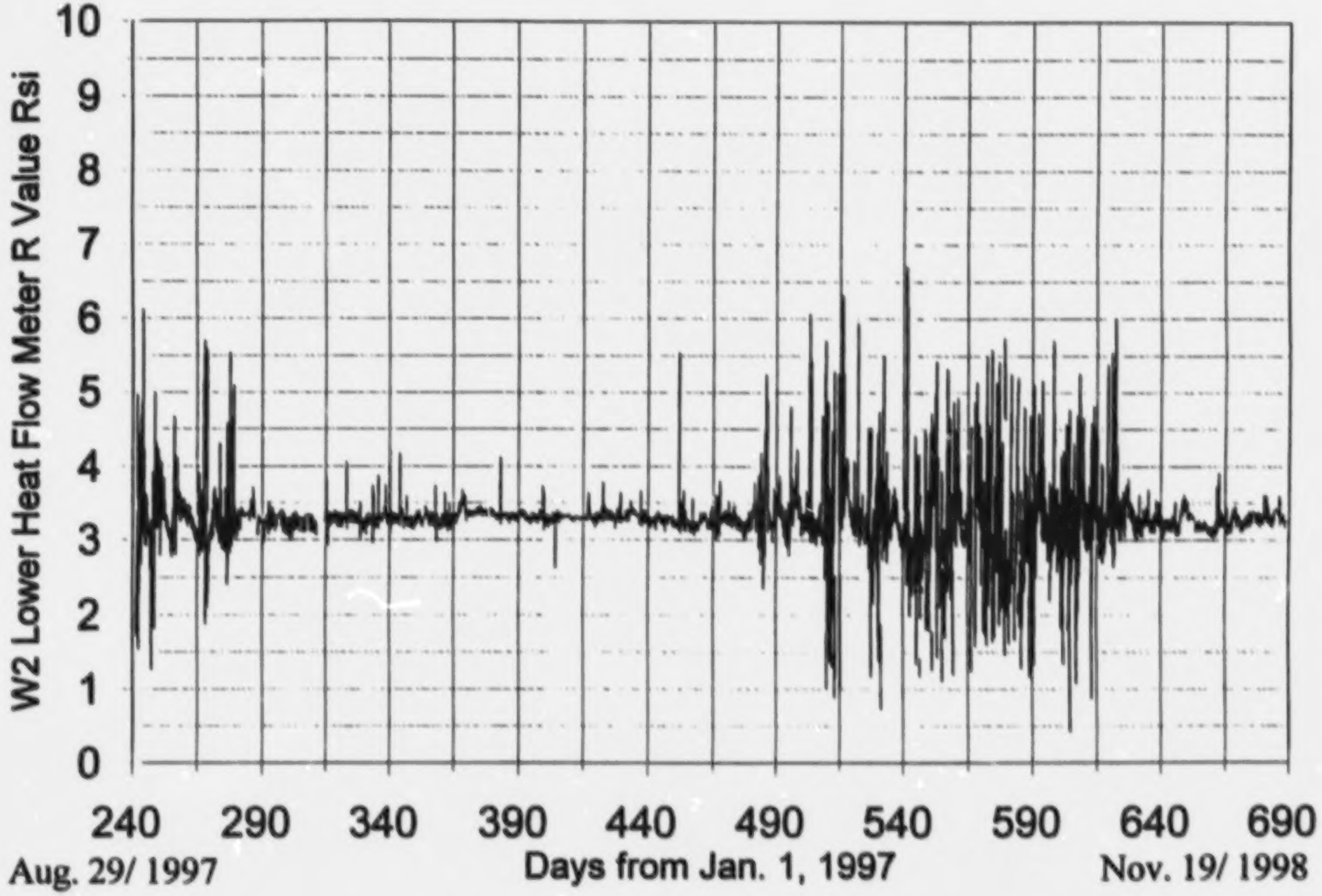


Figure 43. Calculated Insulation RSI value at location W2 (Lower).

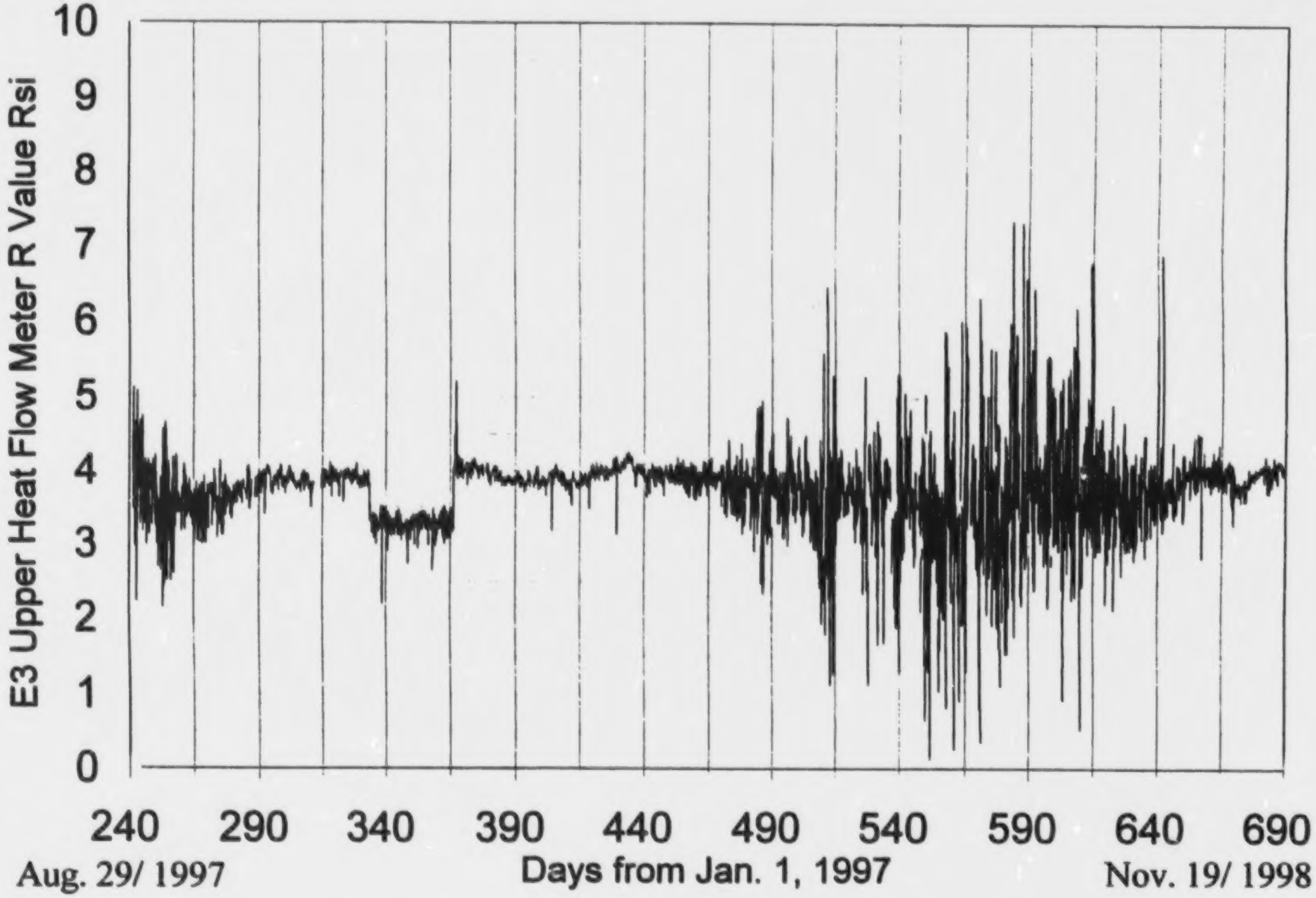


Figure 44. Calculated Insulation RSI value at location E3 (Upper).

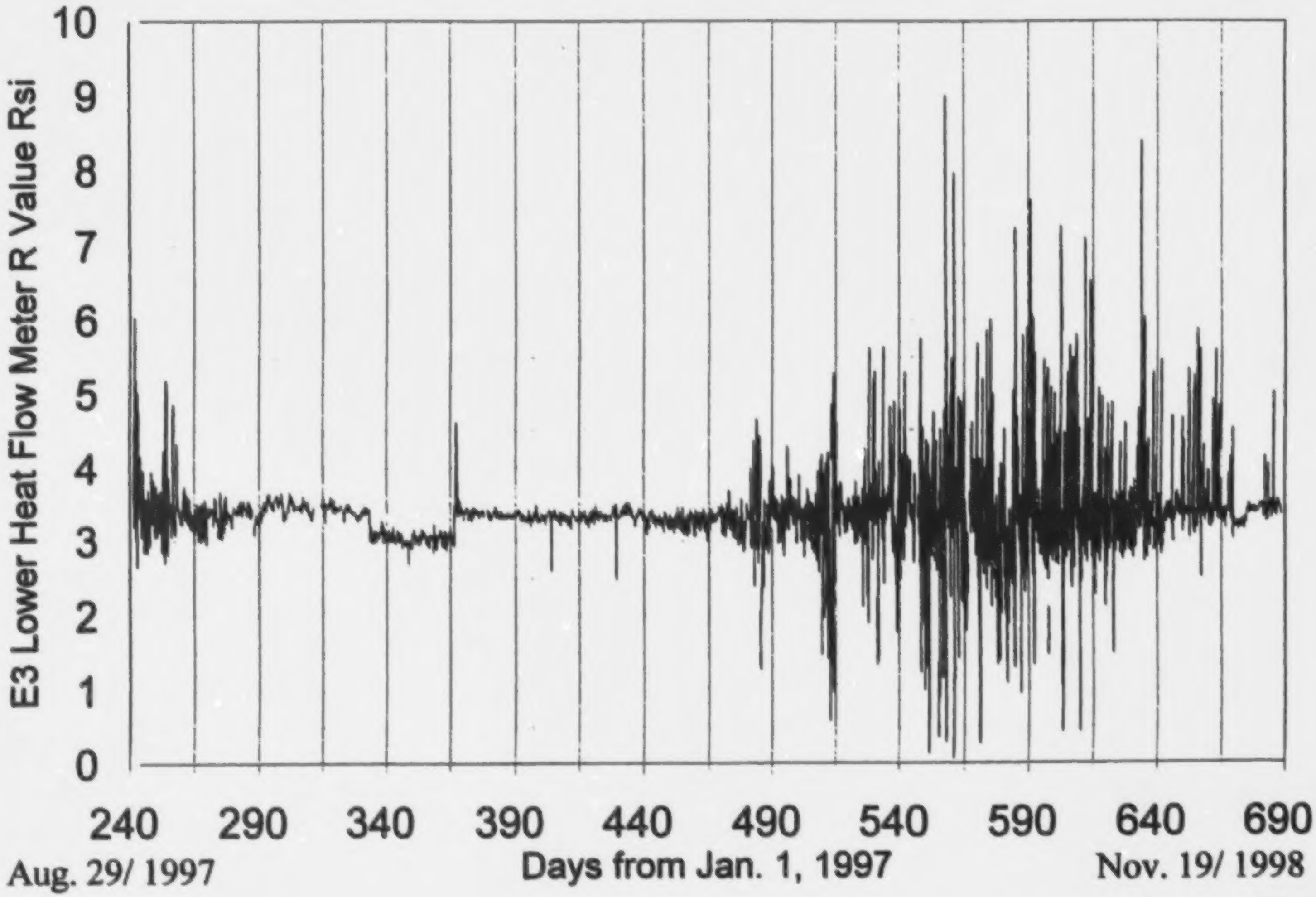


Figure 45. Calculated Insulation RSI value at location E3 (Lower).

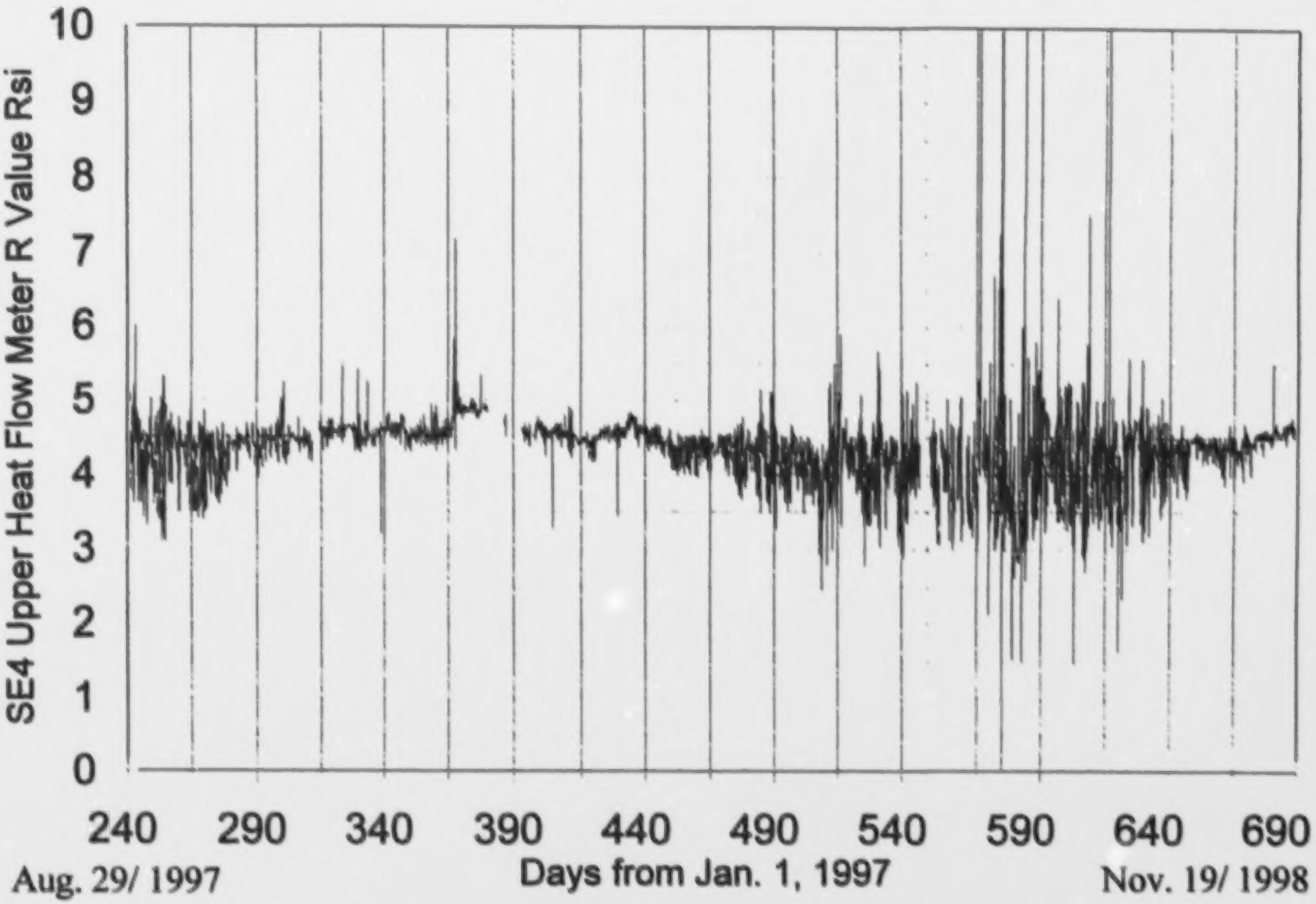


Figure 46. Calculated Insulation RSI value at location SE4 (Upper).

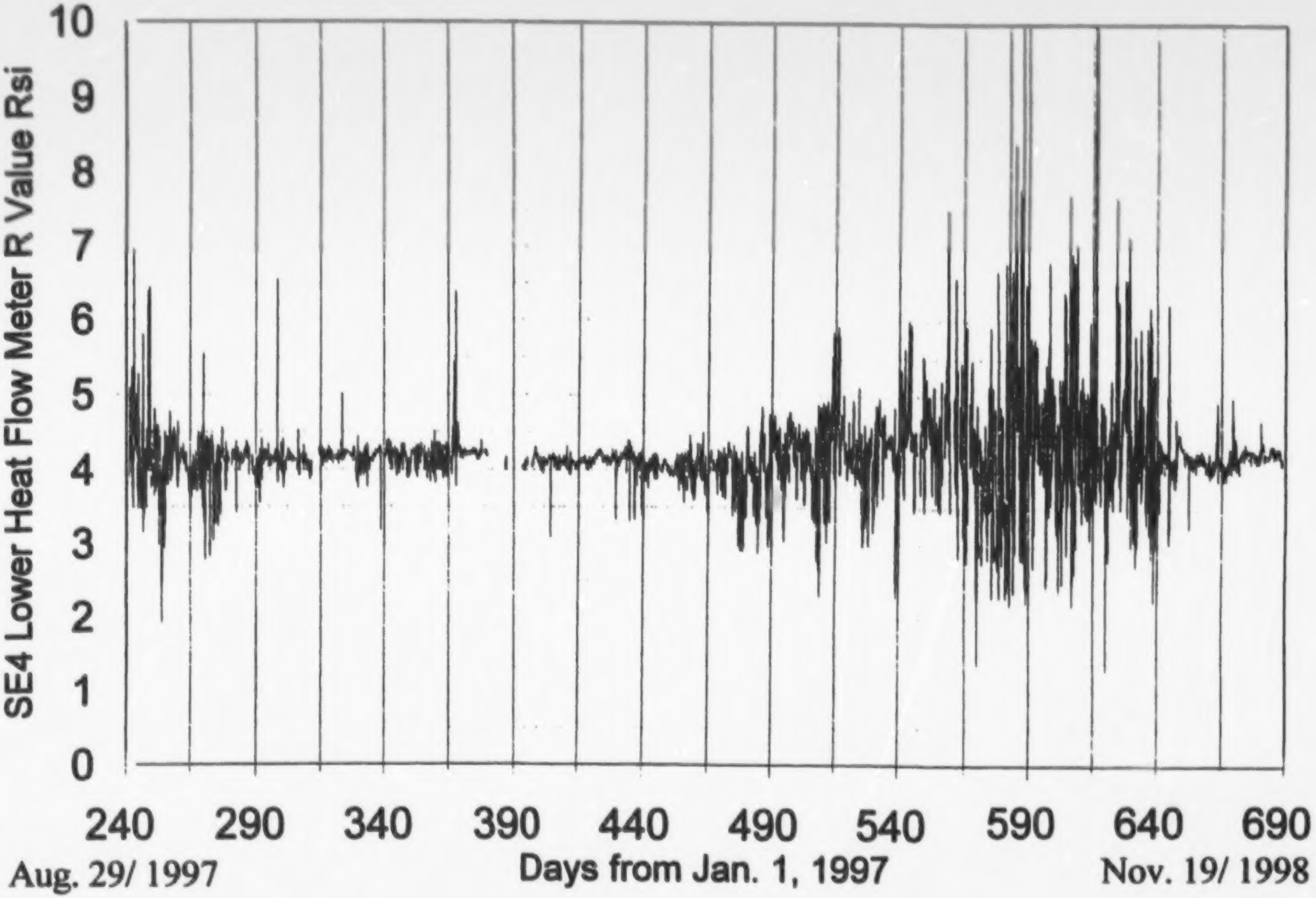


Figure 47. Calculated Insulation RSI value at location SE4 (Lower).

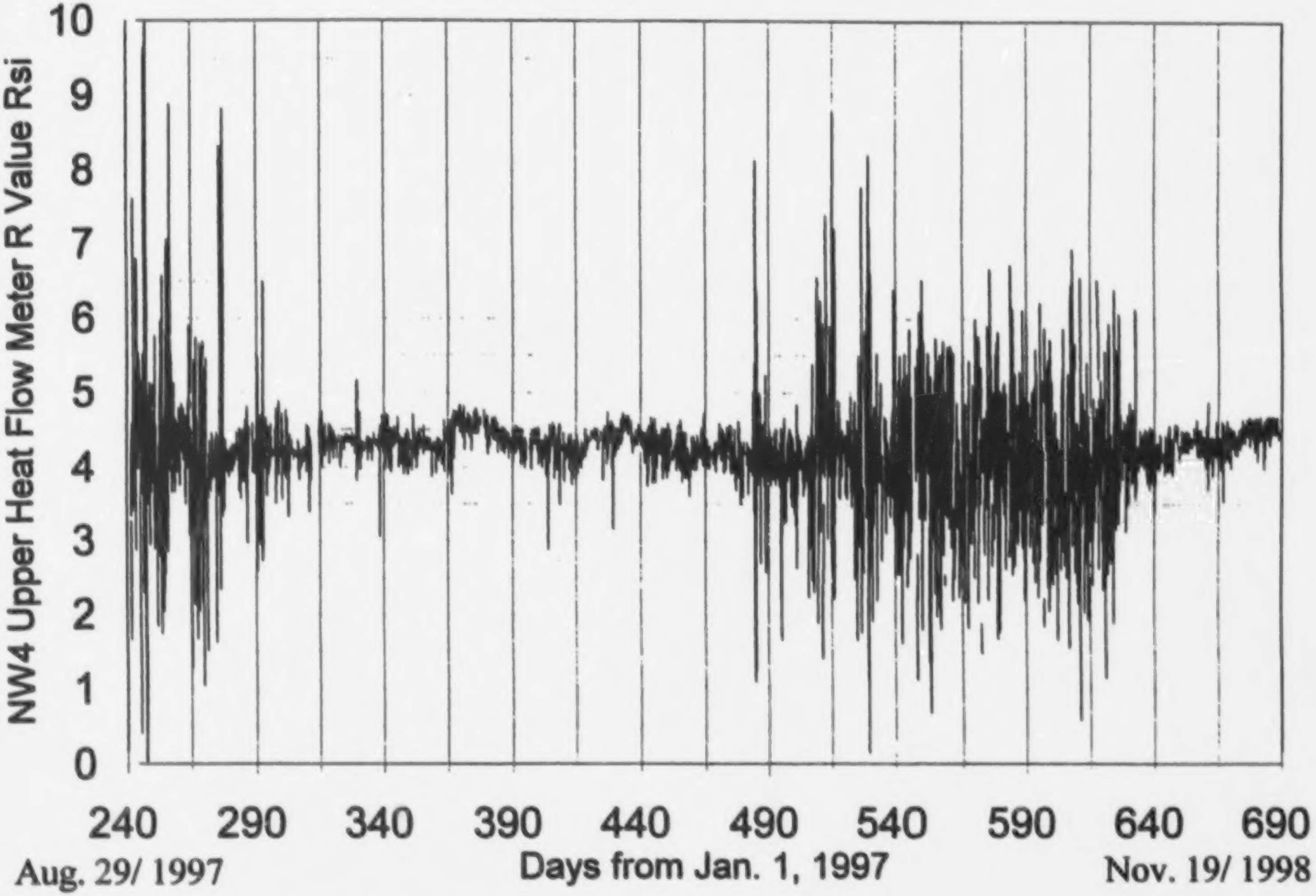


Figure 48. Calculated Insulation RSI value at location NW4(Upper).

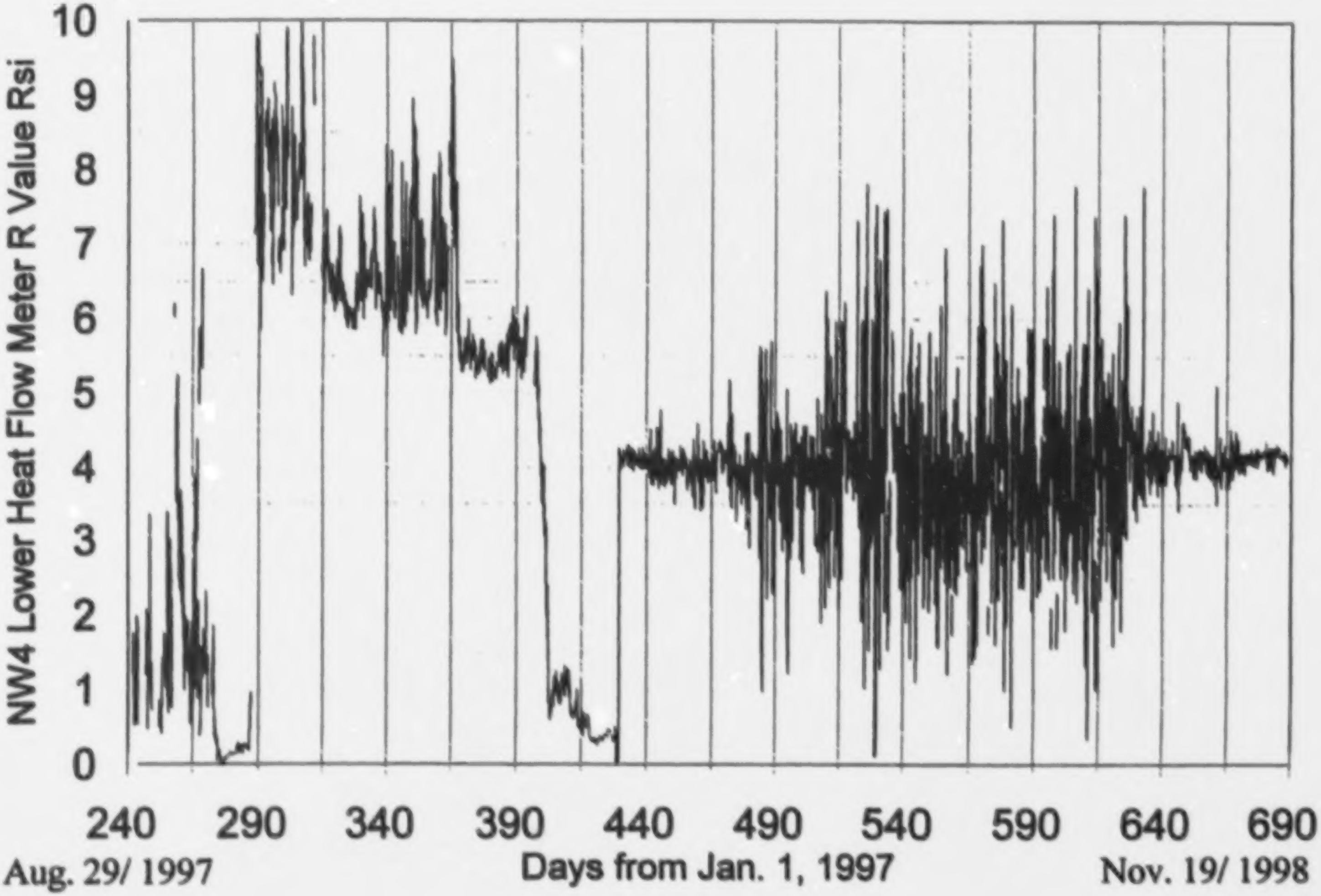


Figure 49. Calculated Insulation RSI value at location NW4(Lower).

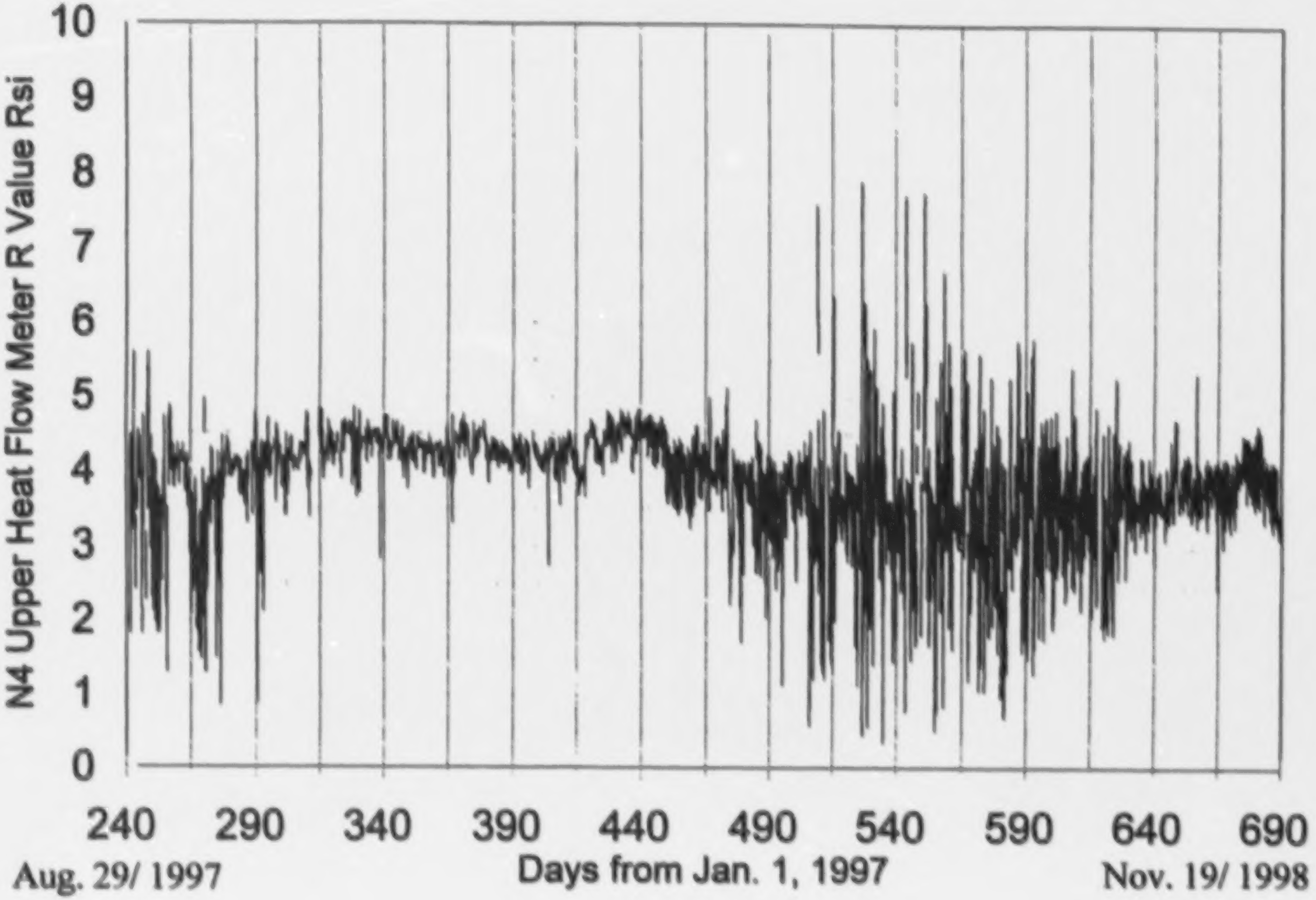


Figure 50. **Calculated Insulation *RSI* value at location N4(Upper).**

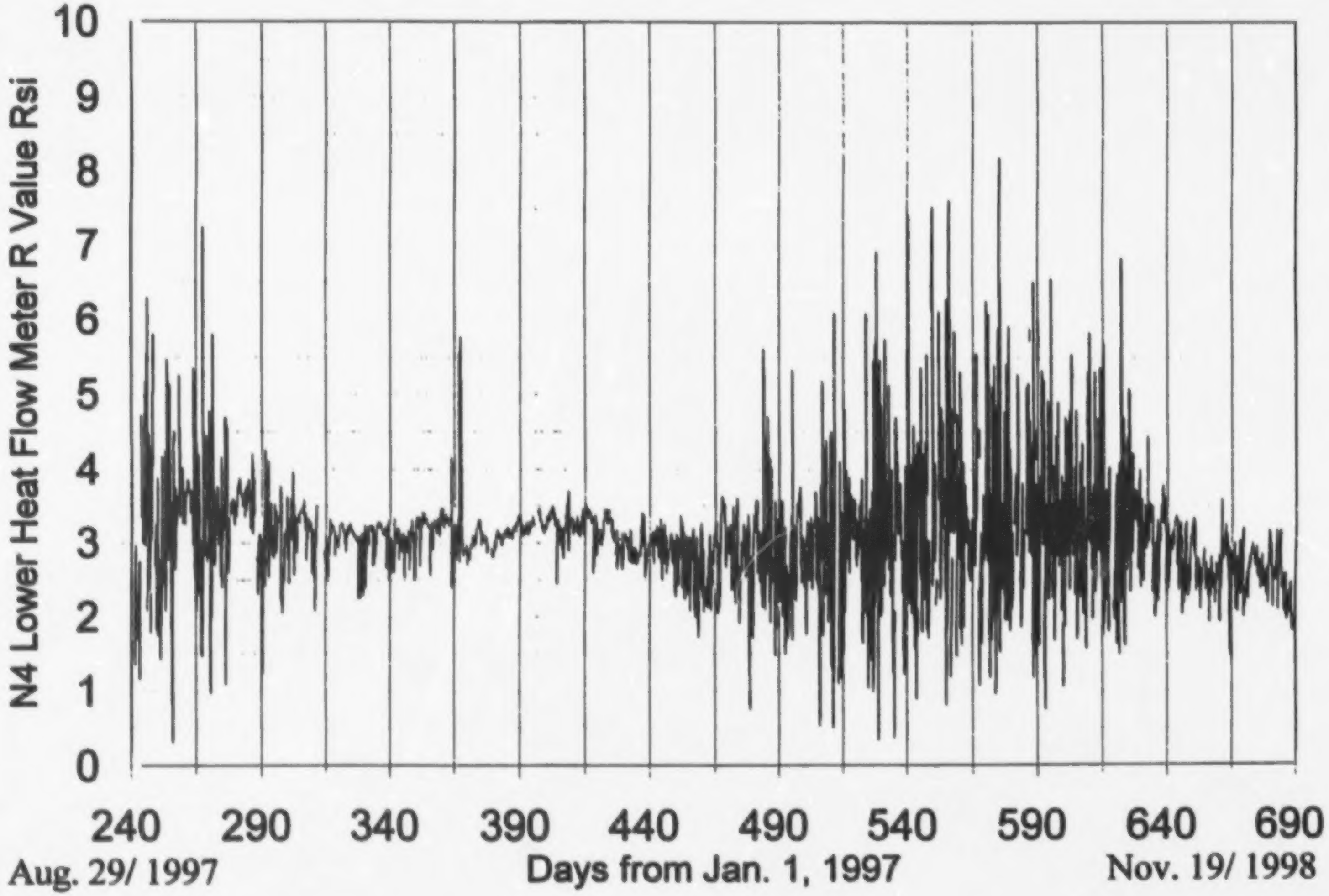


Figure 51. Calculated Insulation RSI value at location N4(Lower).

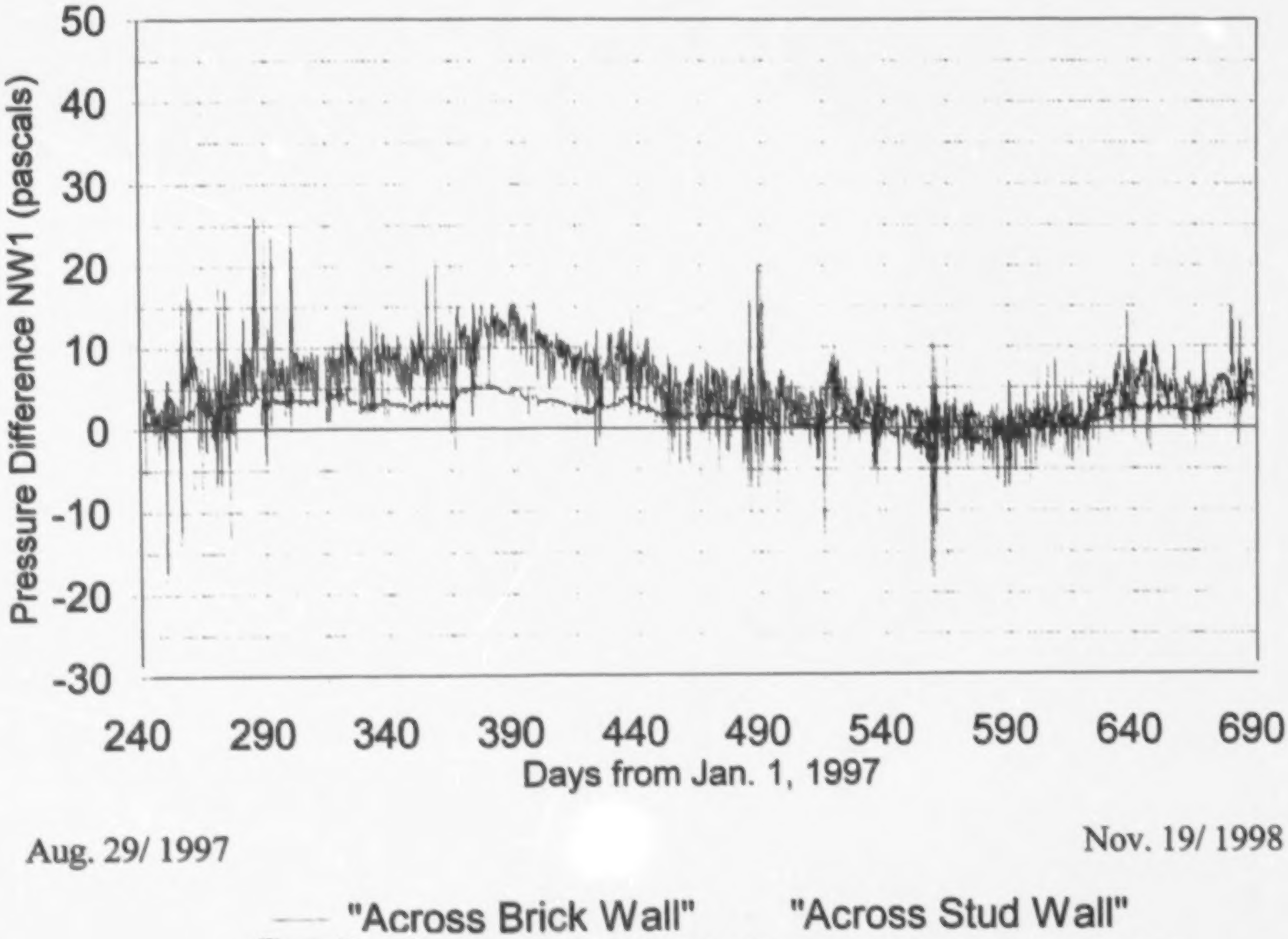


Figure 52. Pressure differences across the brick wall and the stud wall at location NW1.

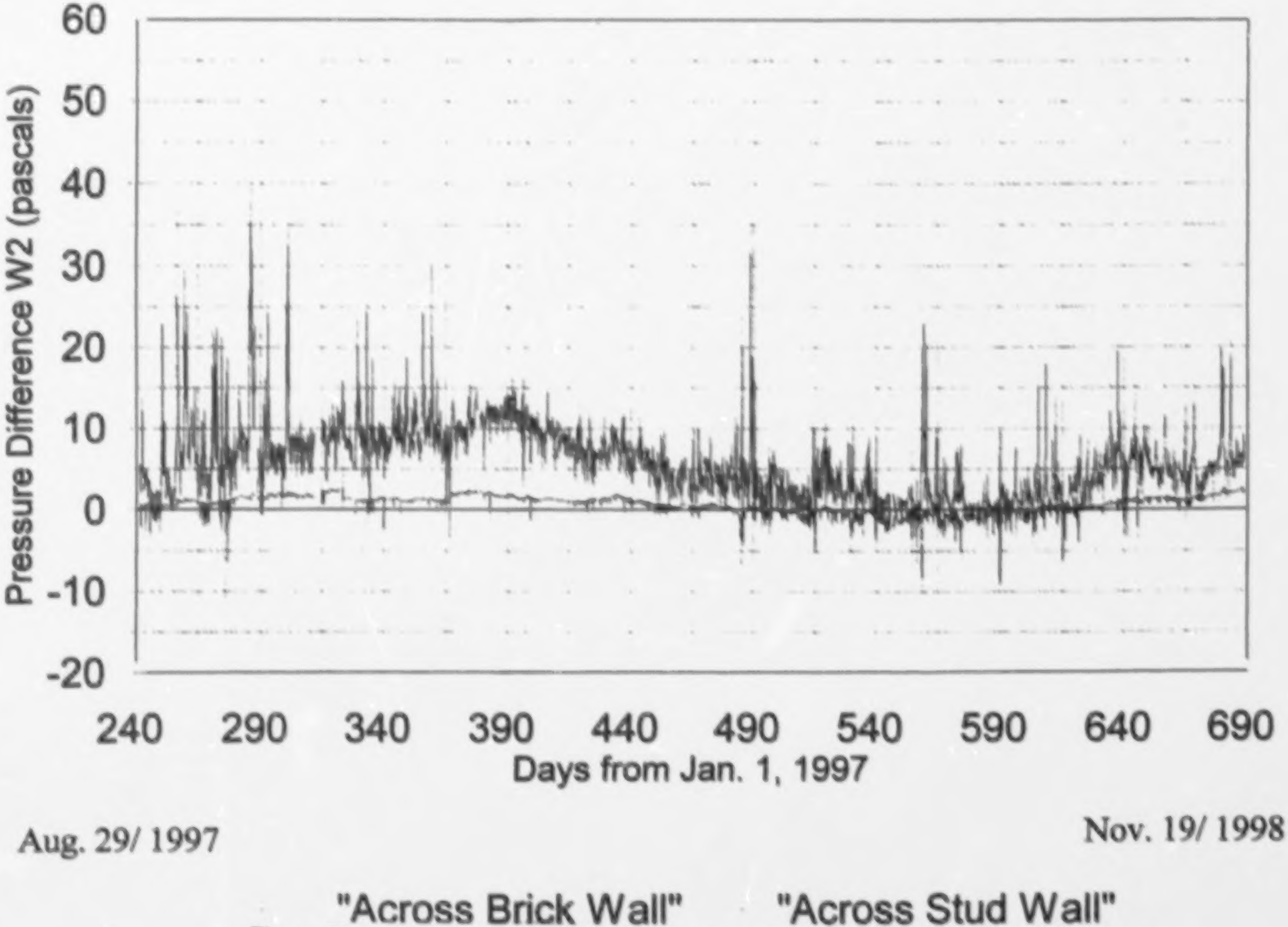


Figure 53. Pressure differences across the brick wall and the stud wall at location W2

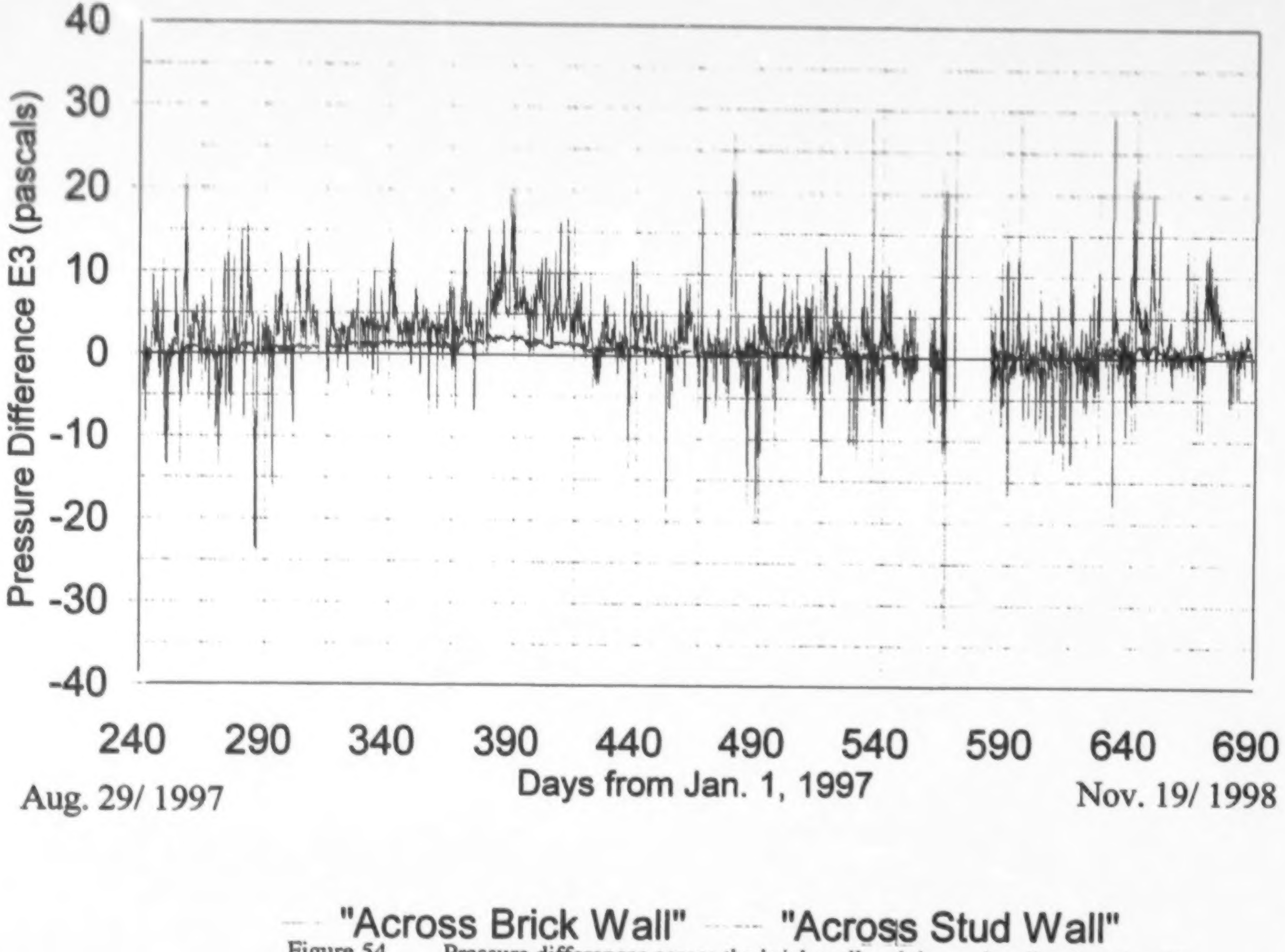


Figure 54. Pressure differences across the brick wall and the stud wall at location E3.

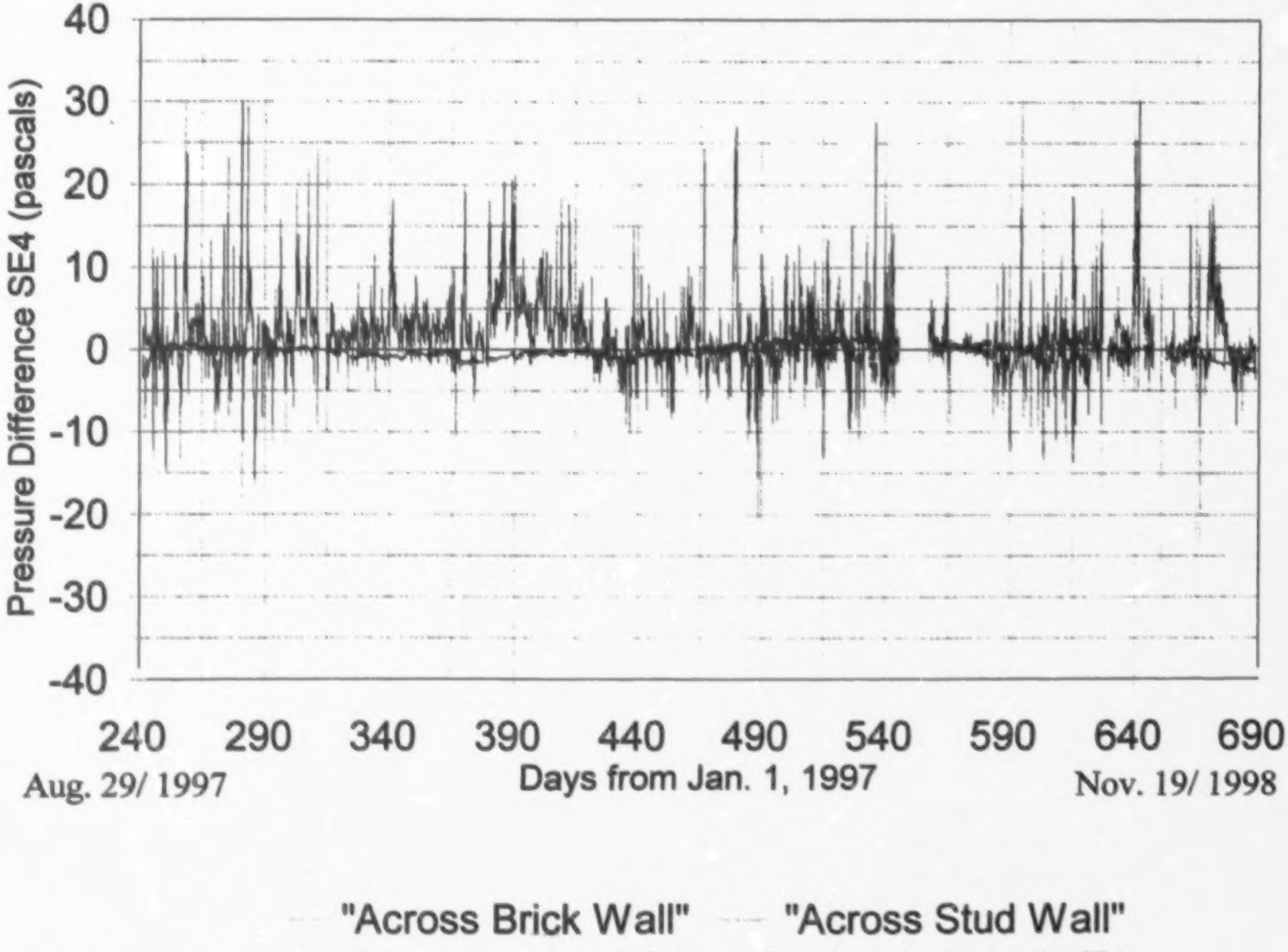


Figure 55. Pressure differences across the brick wall and the stud wall at location SE4.

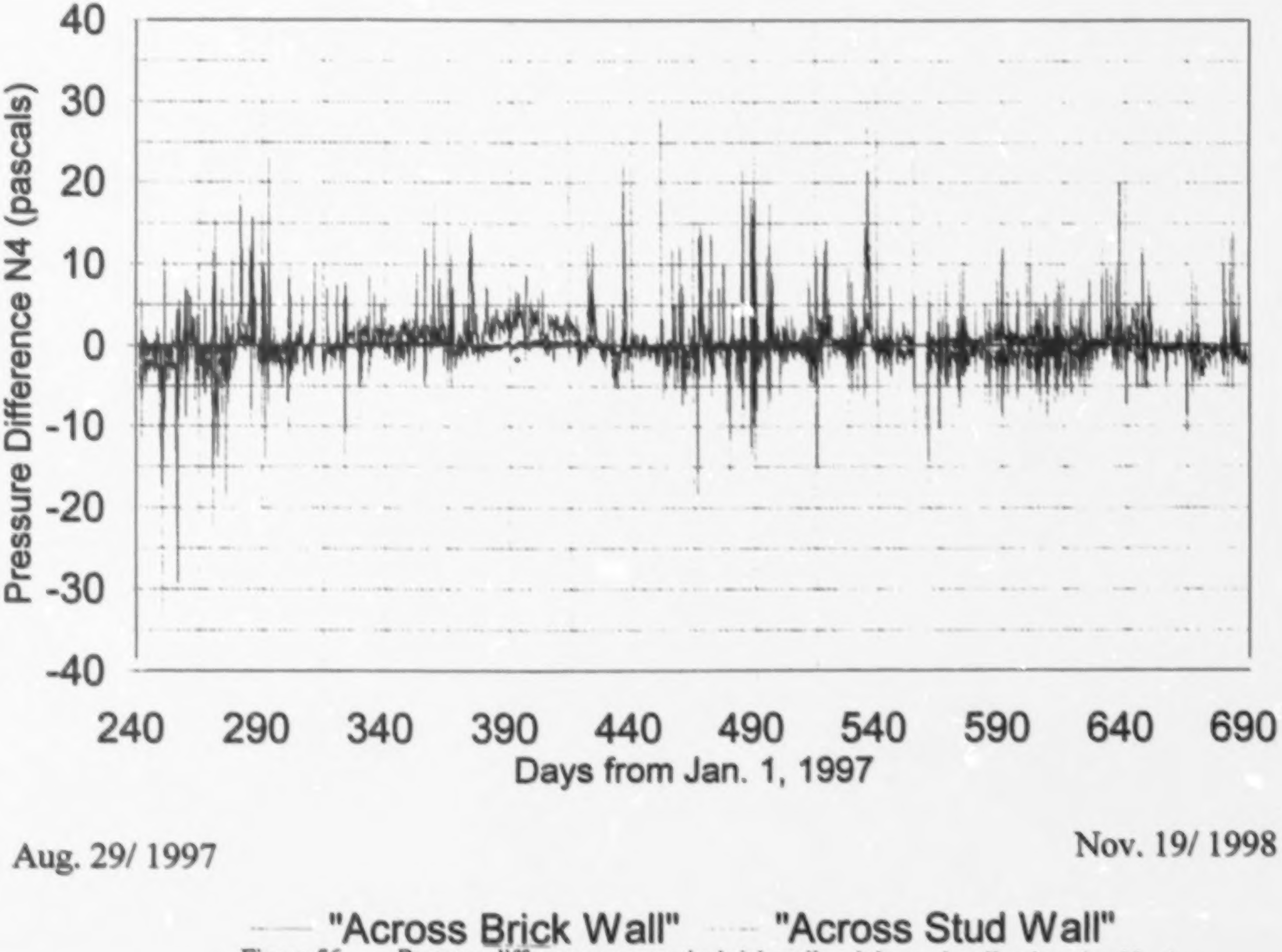


Figure 56. Pressure differences across the brick wall and the stud wall at location N 4.

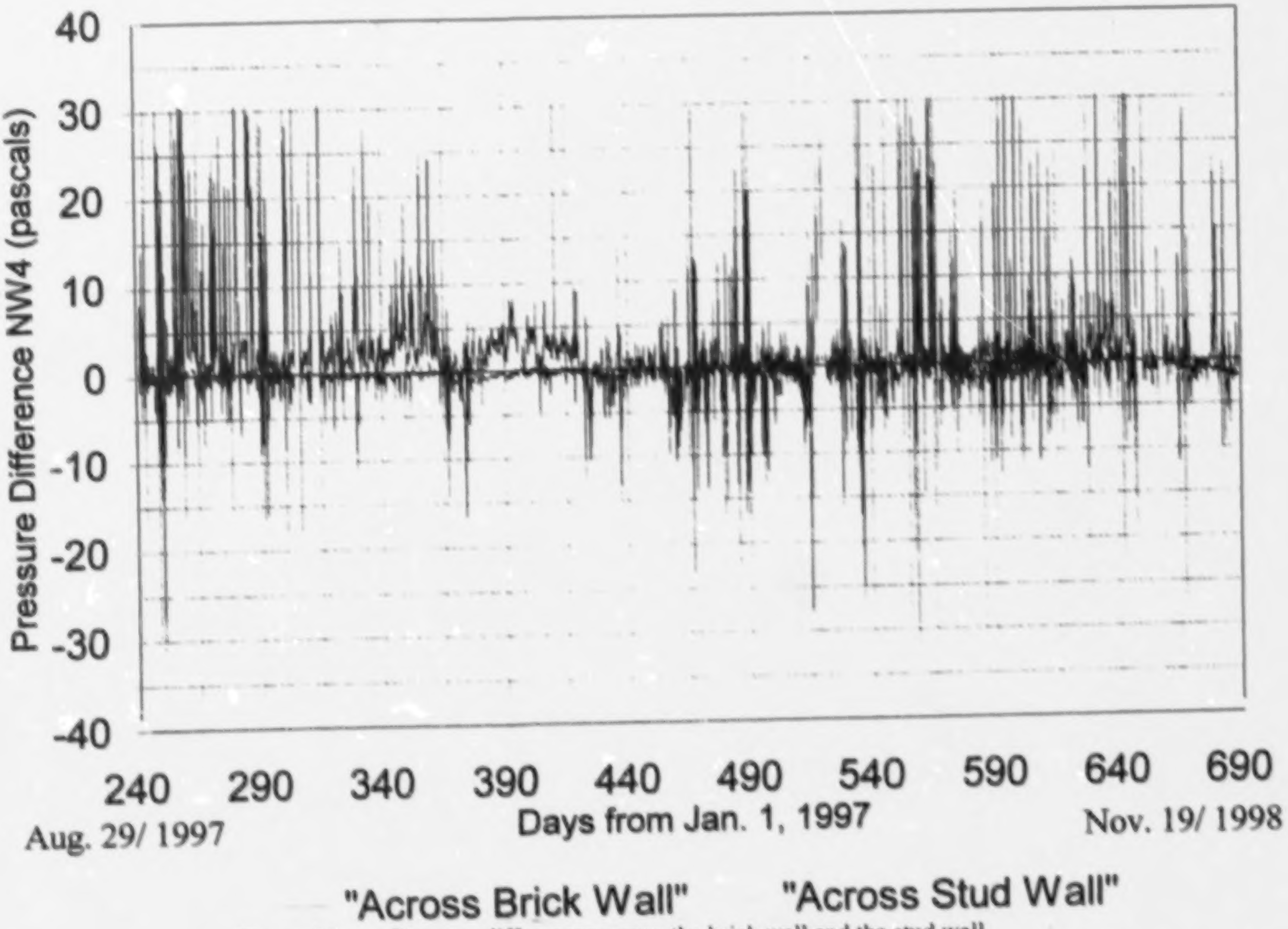


Figure 57. Pressure differences across the brick wall and the stud wall

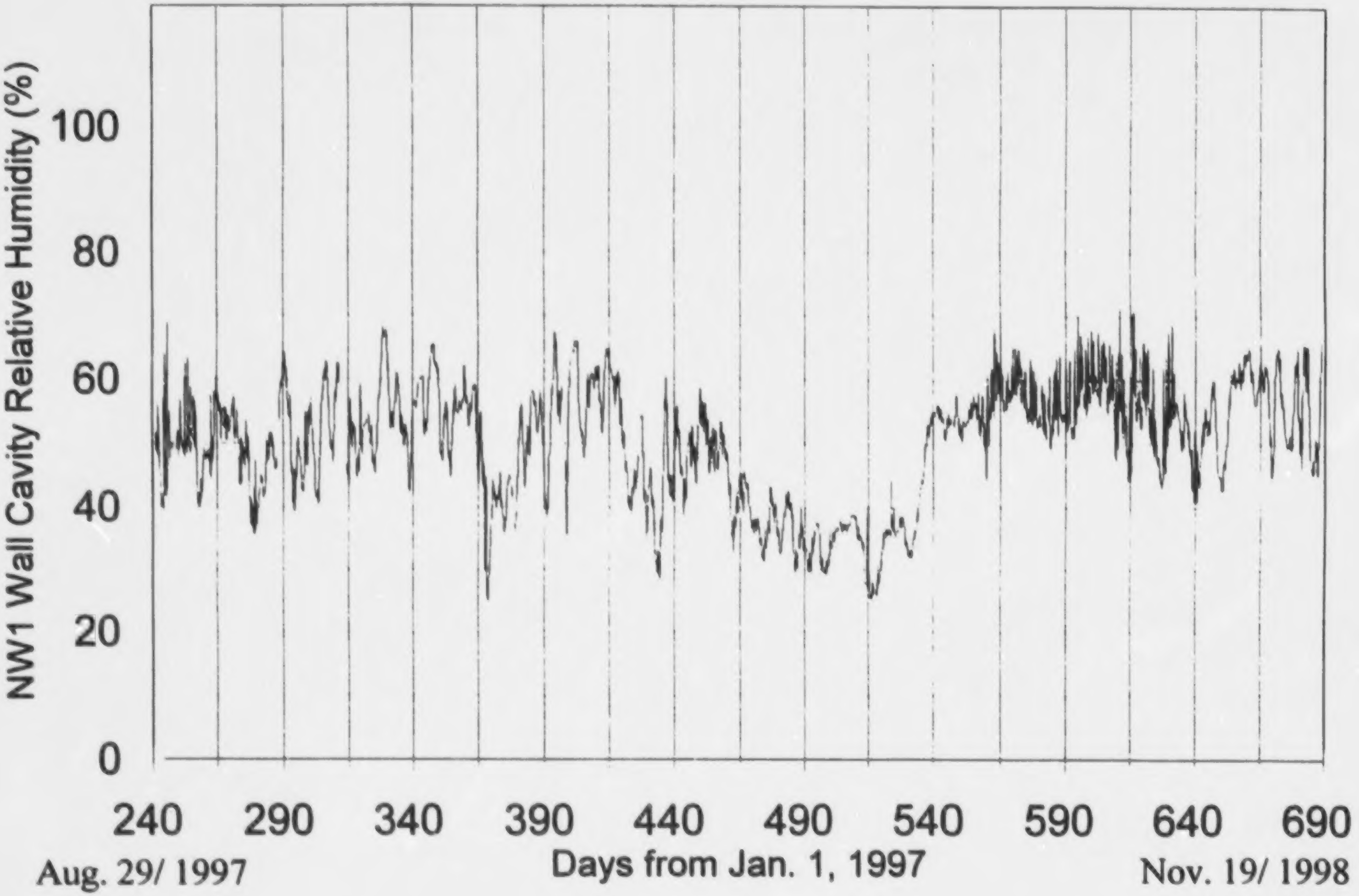


Figure 58. Wall cavity relative humidity at location NW1.

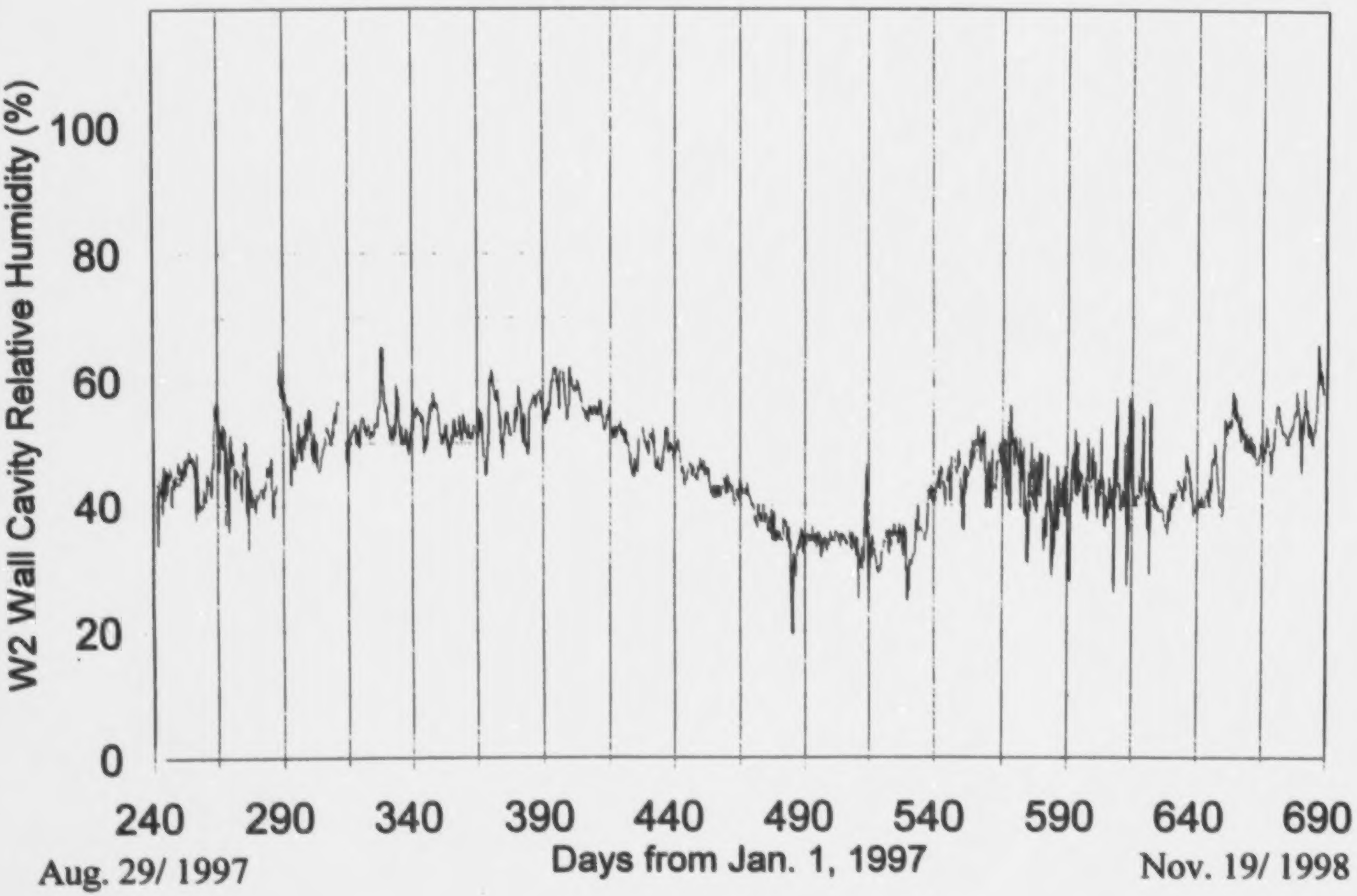


Figure 59. Wall cavity relative humidity at location W2.

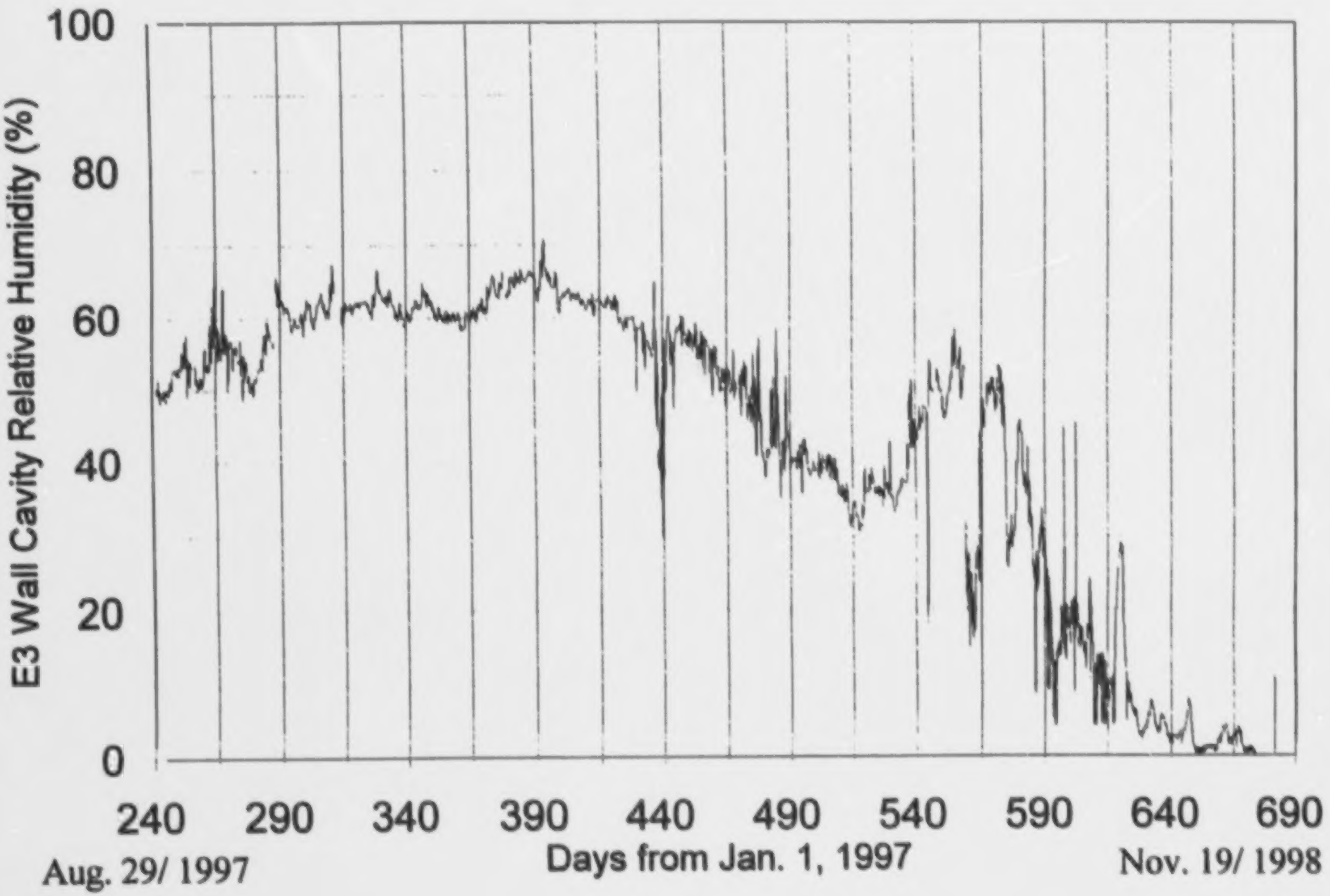


Figure 60. Wall cavity relative humidity at location E3.

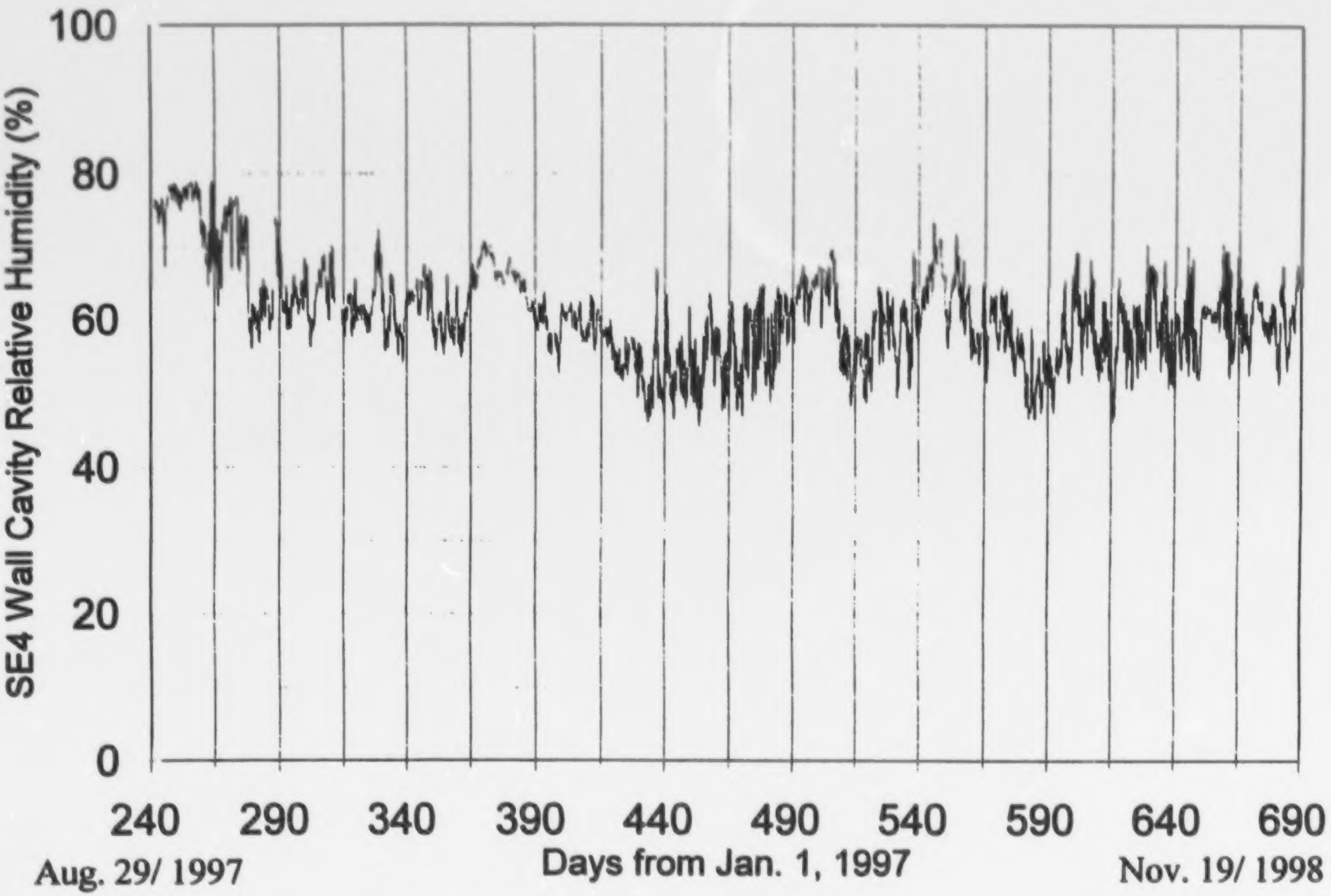


Figure 61. Wall cavity relative humidity at location SE4.

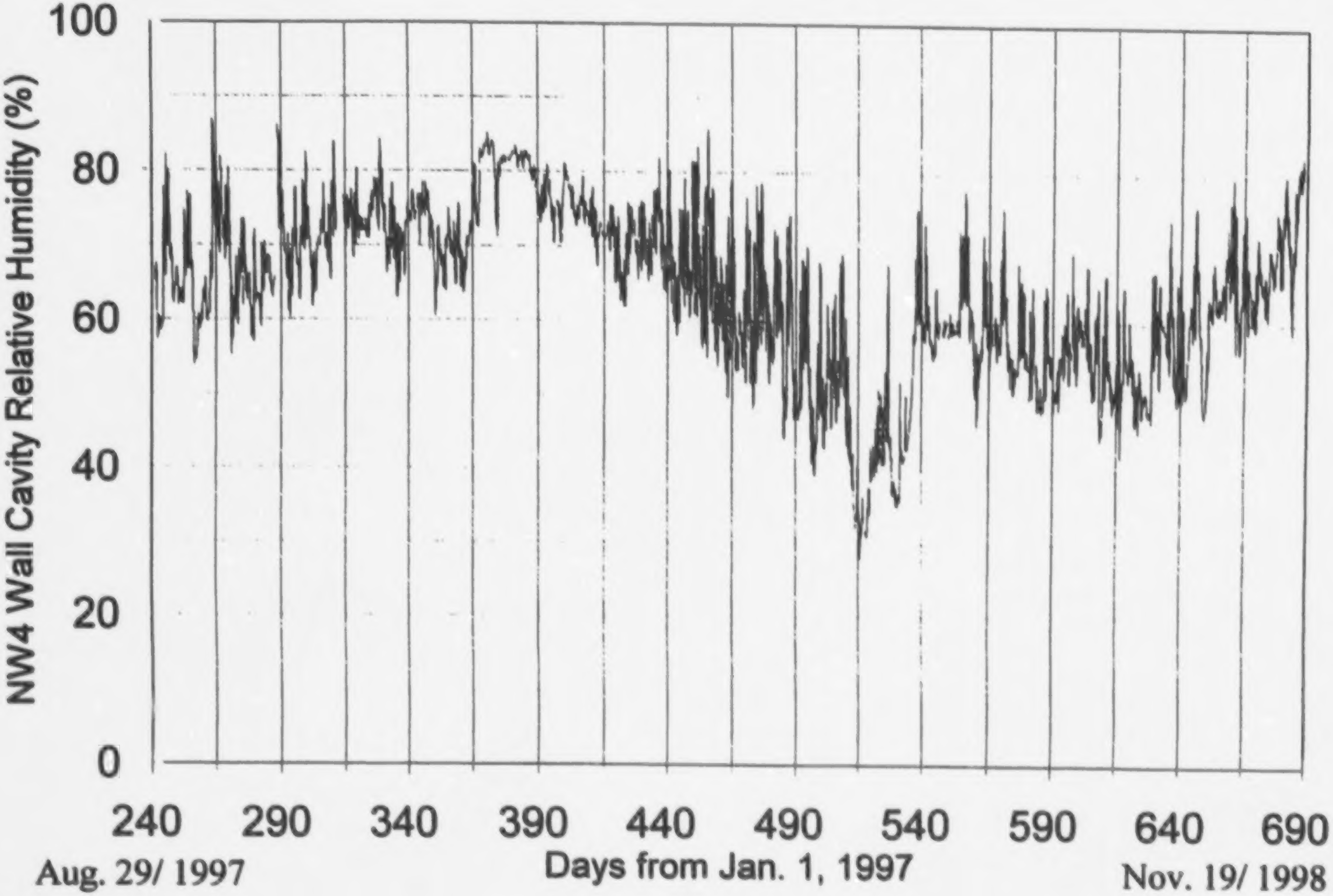


Figure 62. Wall cavity relative humidity at location NW4.

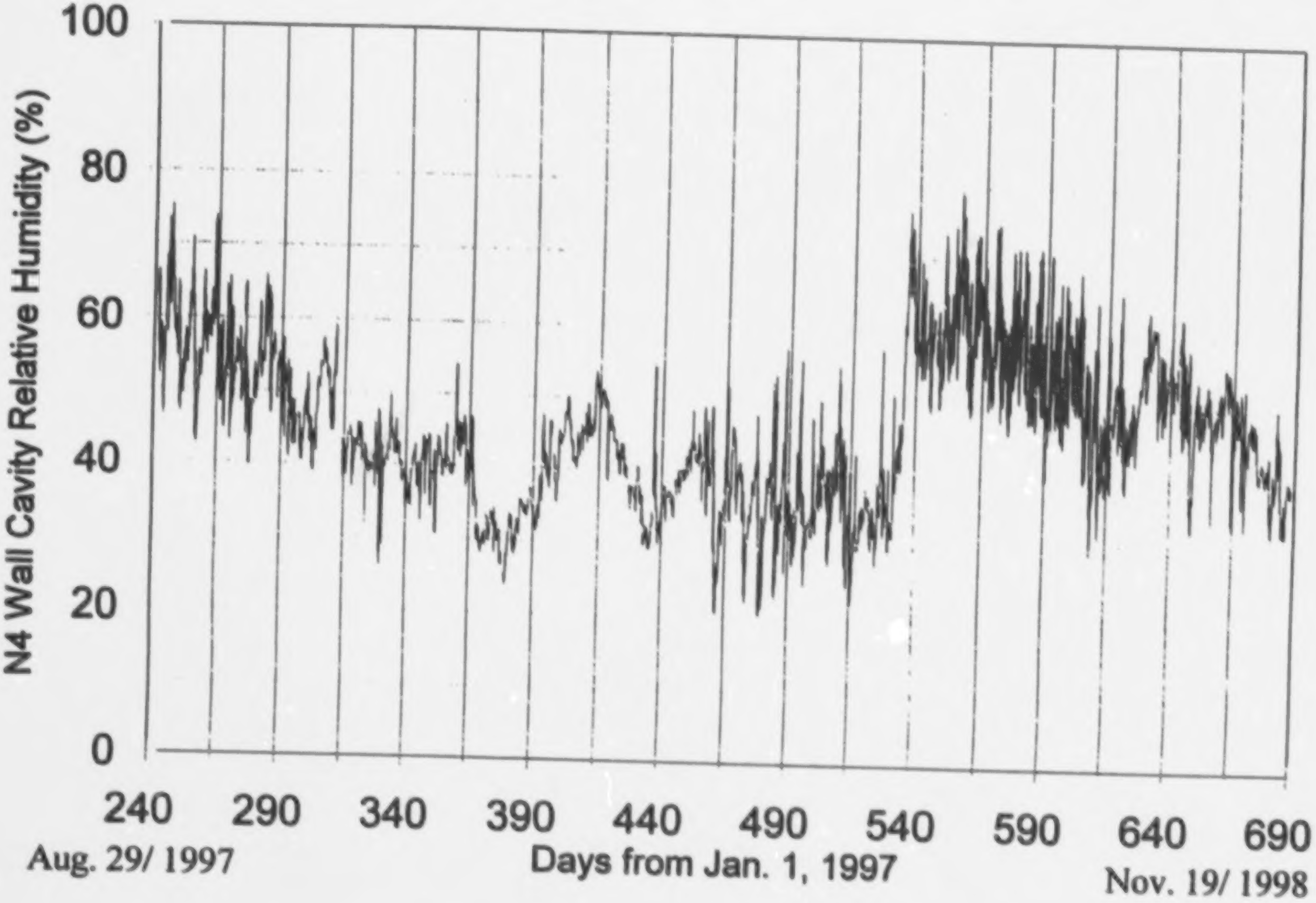


Figure 63. Wall cavity relative humidity at location N4.

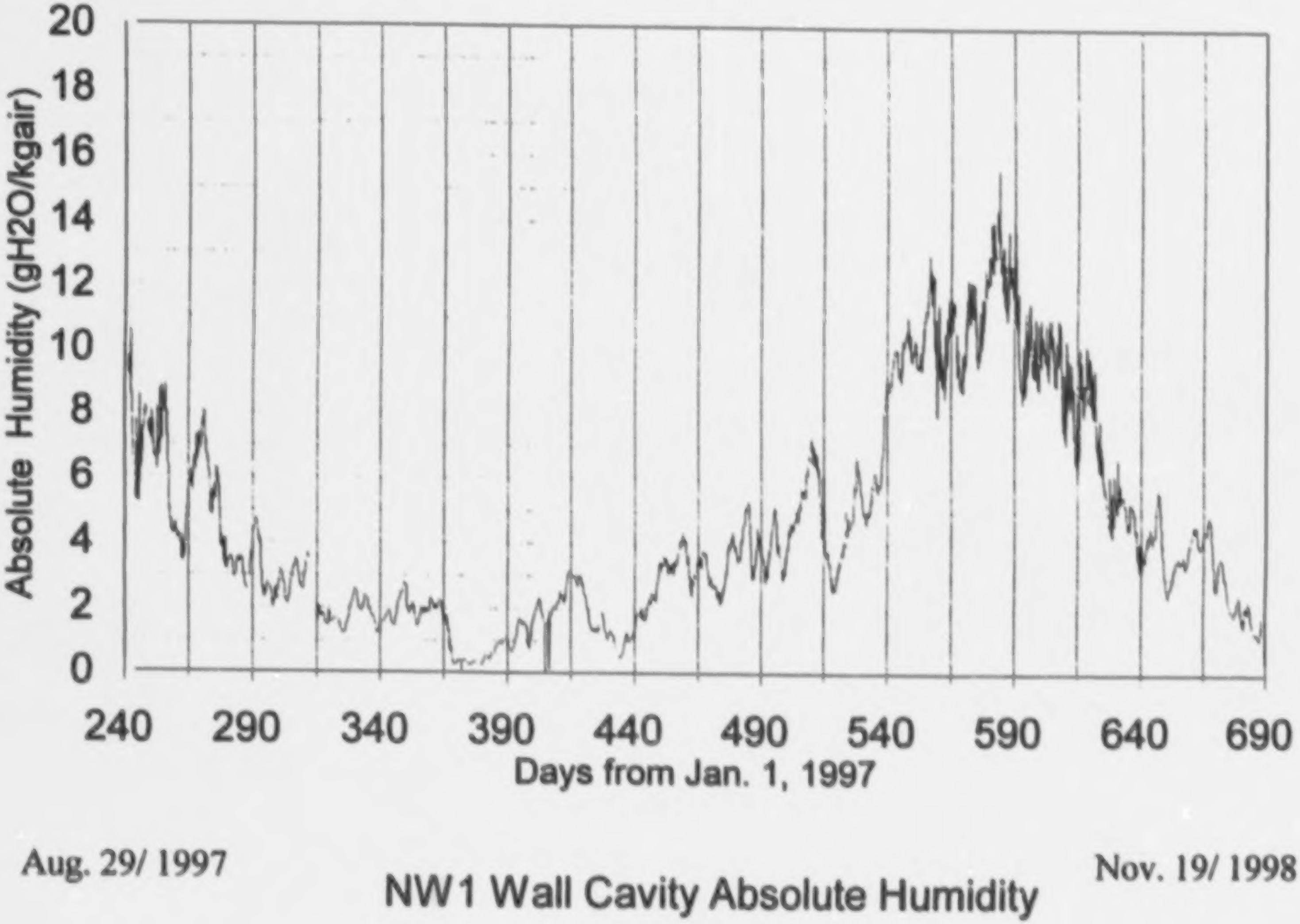


Figure 64. Wall cavity absolute humidity at location NW1.

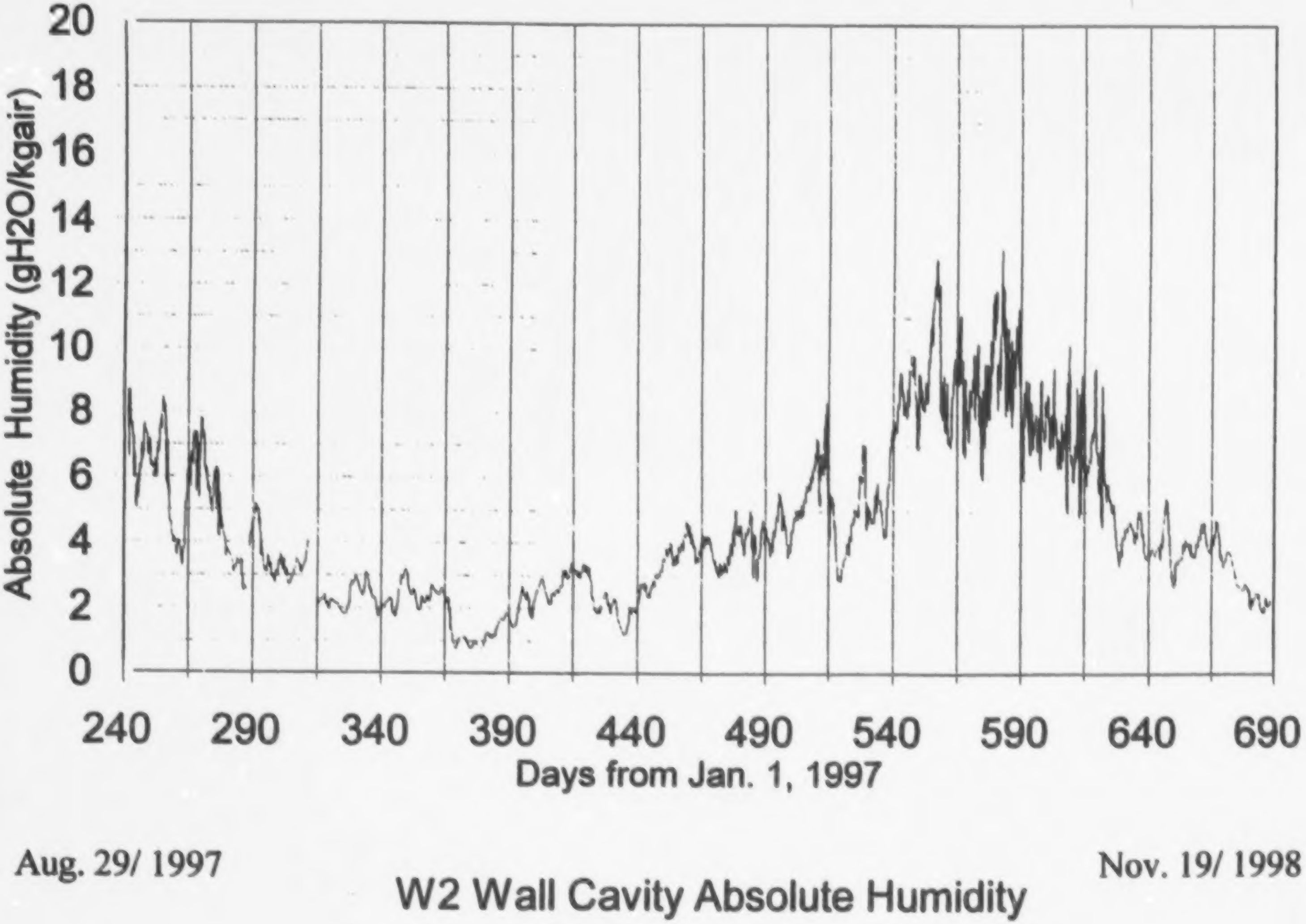


Figure 65. Wall cavity absolute humidity at location W2.

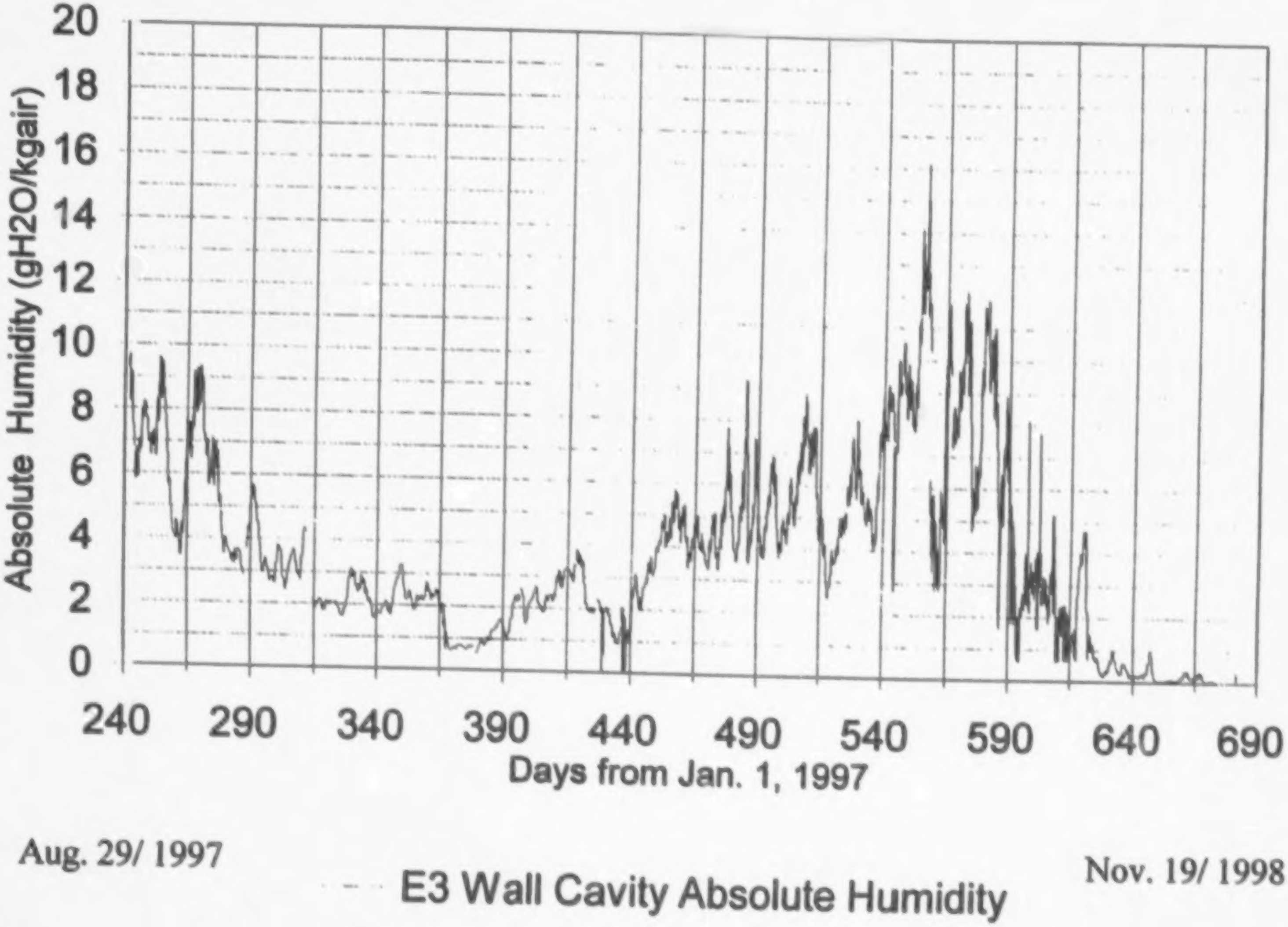


Figure 66. Wall cavity absolute humidity at location E3.

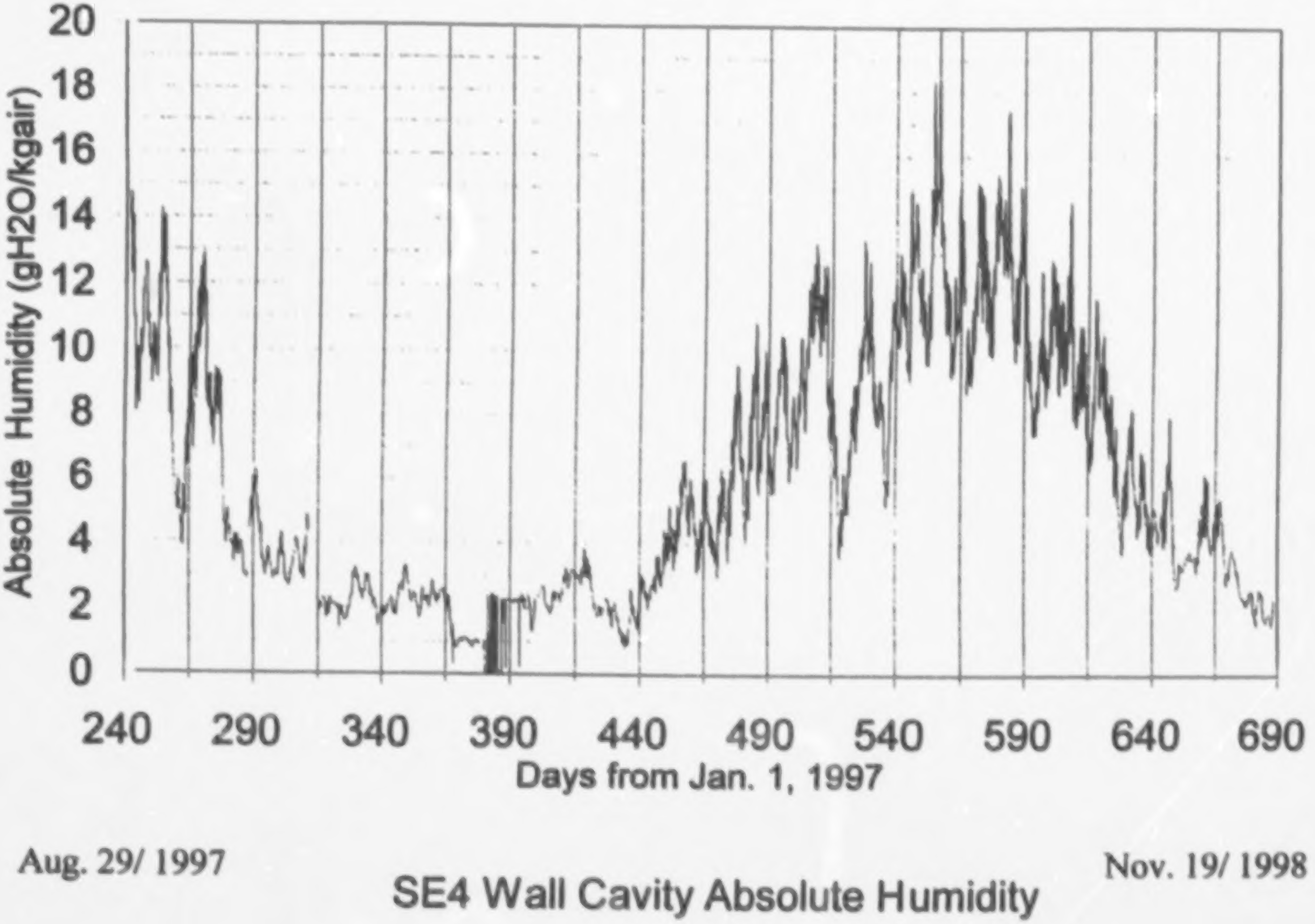


Figure 67. Wall cavity absolute humidity at location SE4.

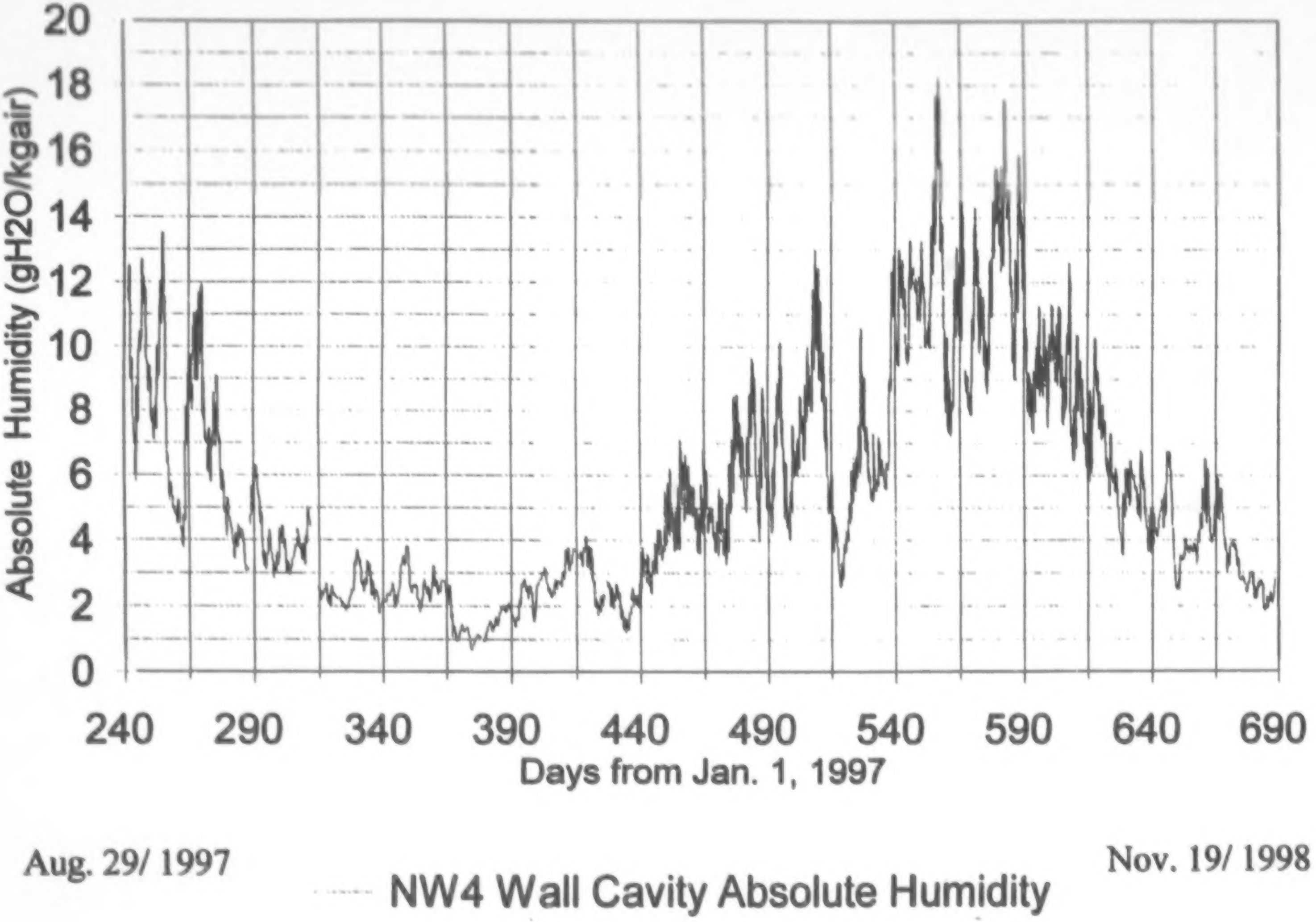


Figure 68. Wall cavity absolute humidity at location NW4.

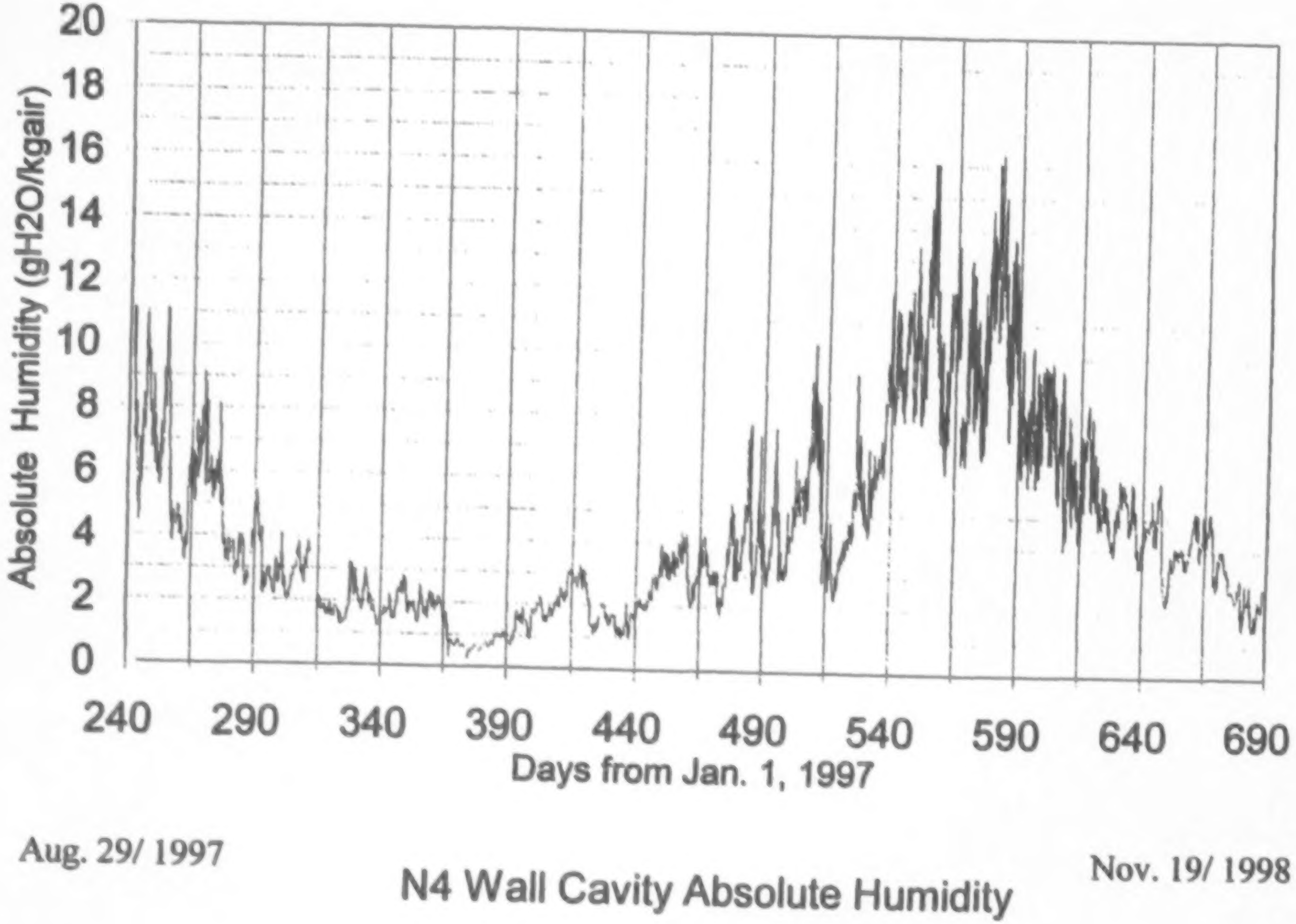


Figure 69. Wall cavity absolute humidity at location N4.

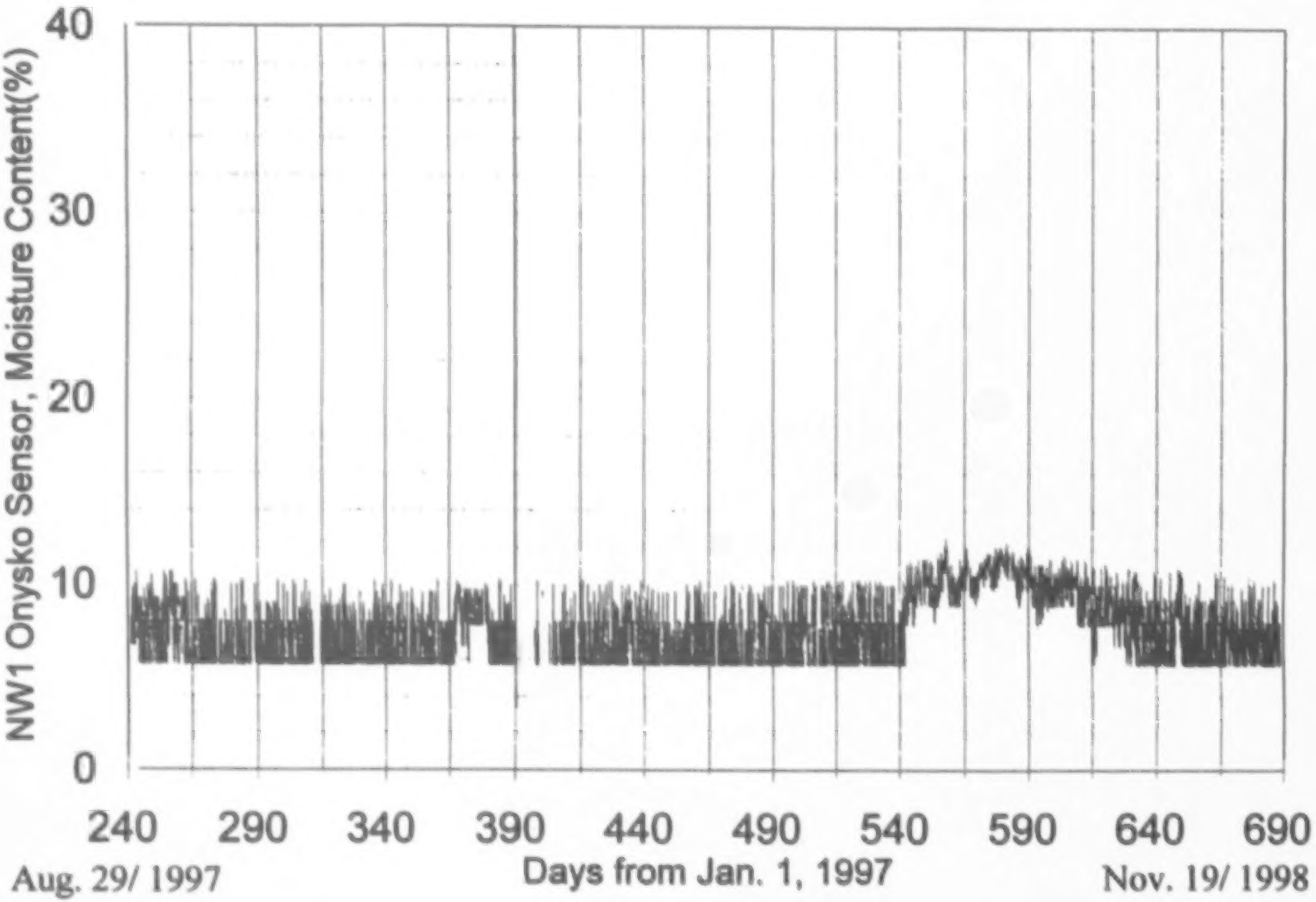


Figure 70. Onysko sensor moisture content at location NW1.

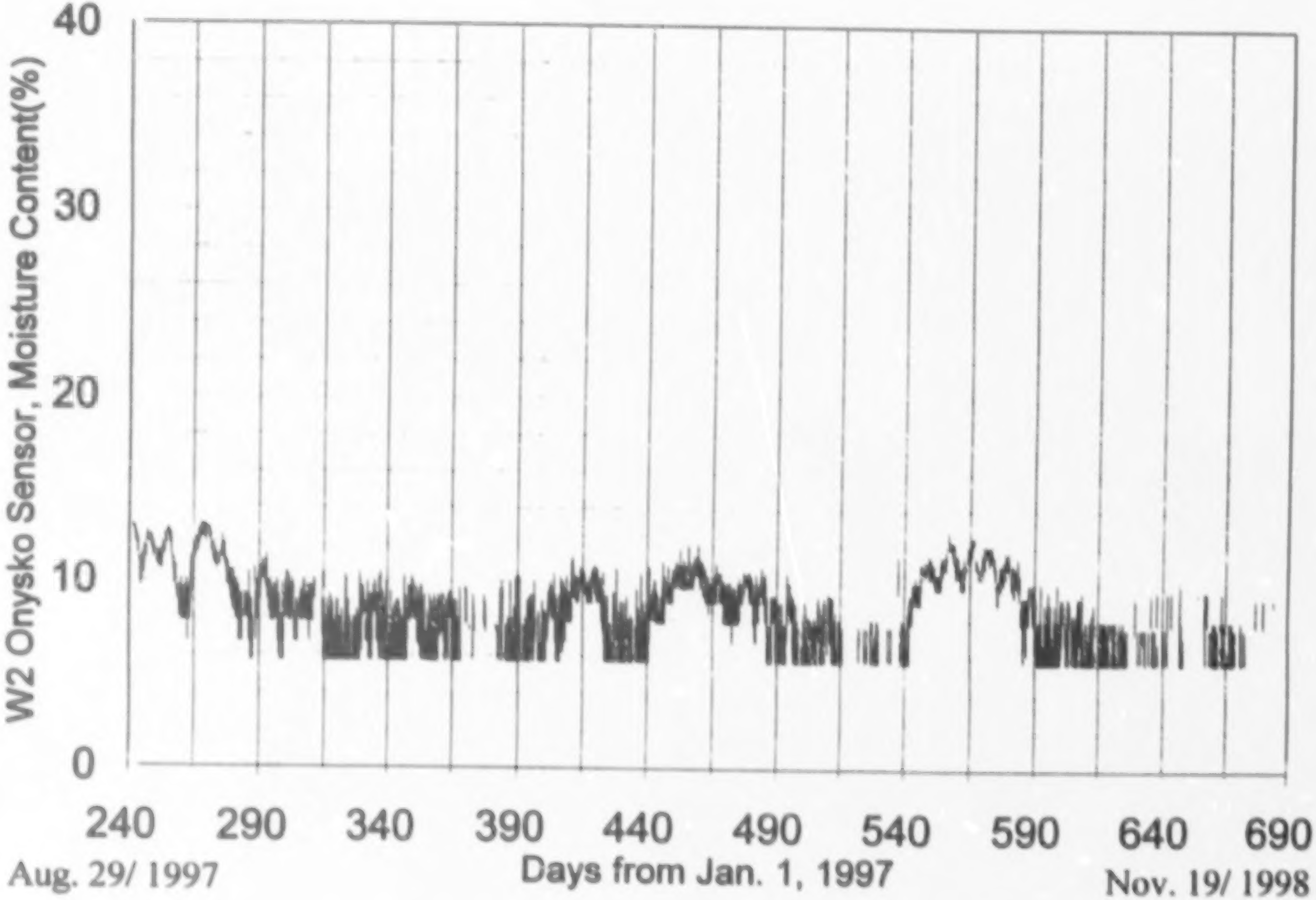


Figure 71. Onysko sensor moisture content at location W2.

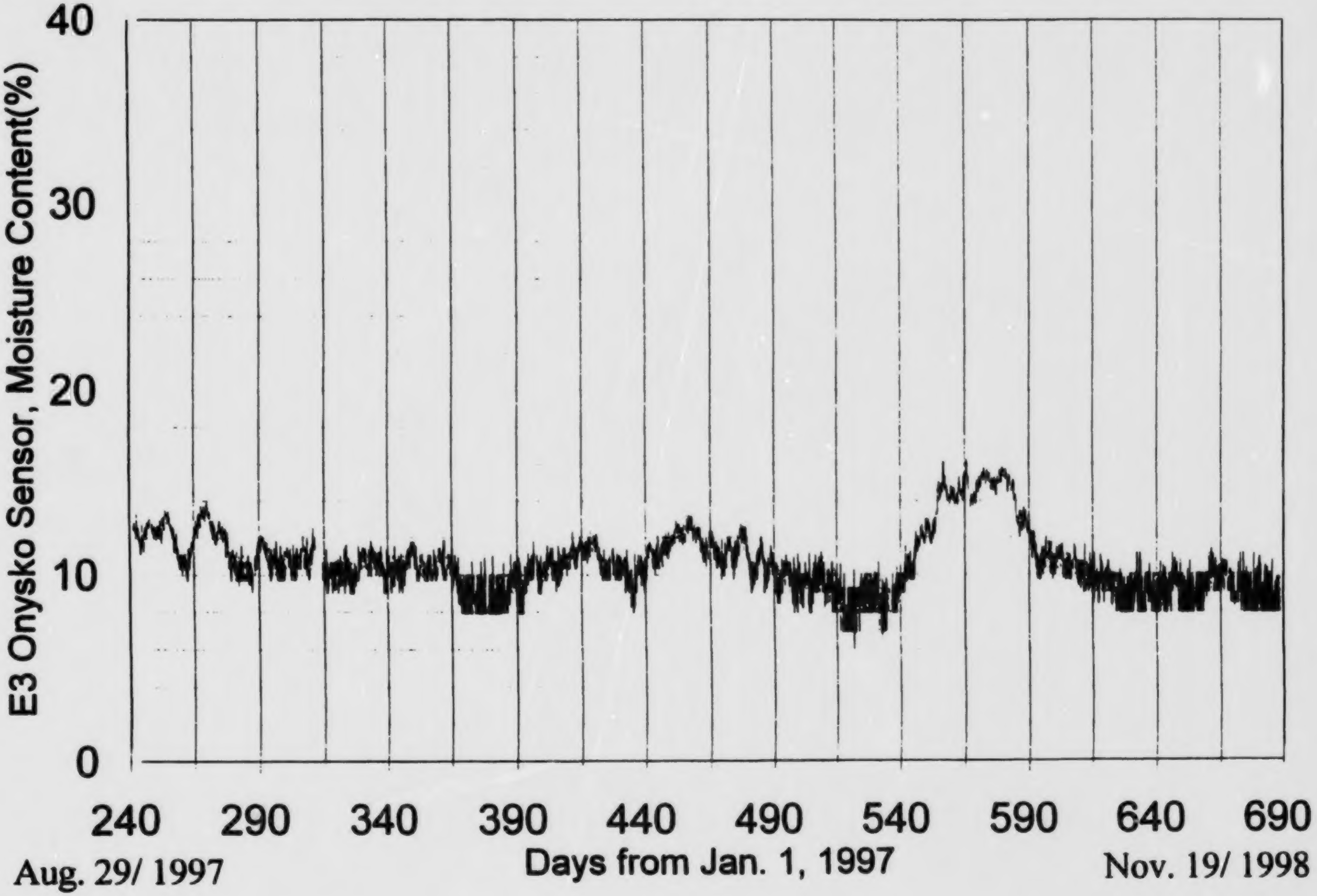


Figure 72. Onysko sensor moisture content at location E3.

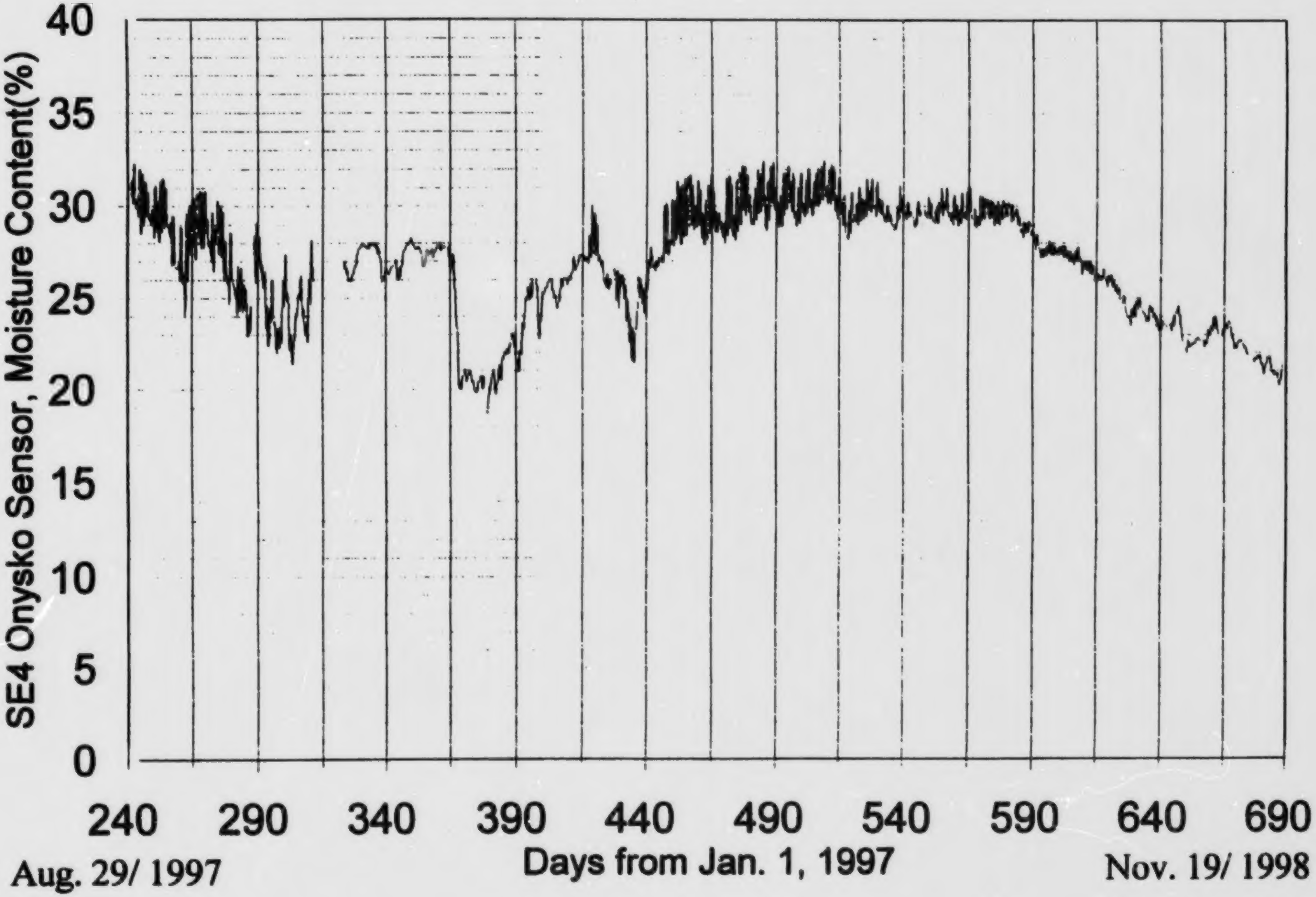


Figure 73. Onysko sensor moisture content at location SE4.

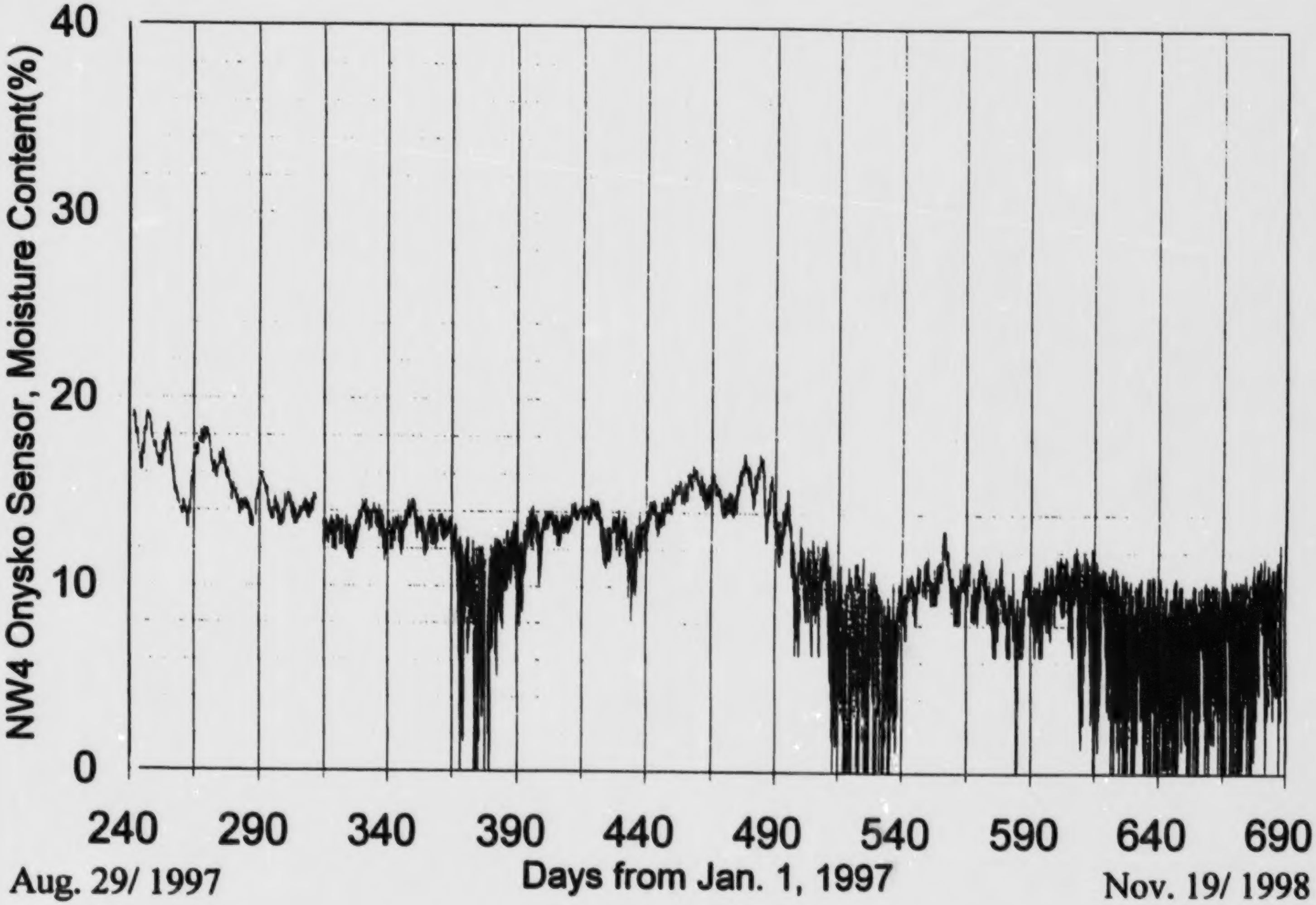


Figure 74. Onysko sensor moisture content at location NW4.

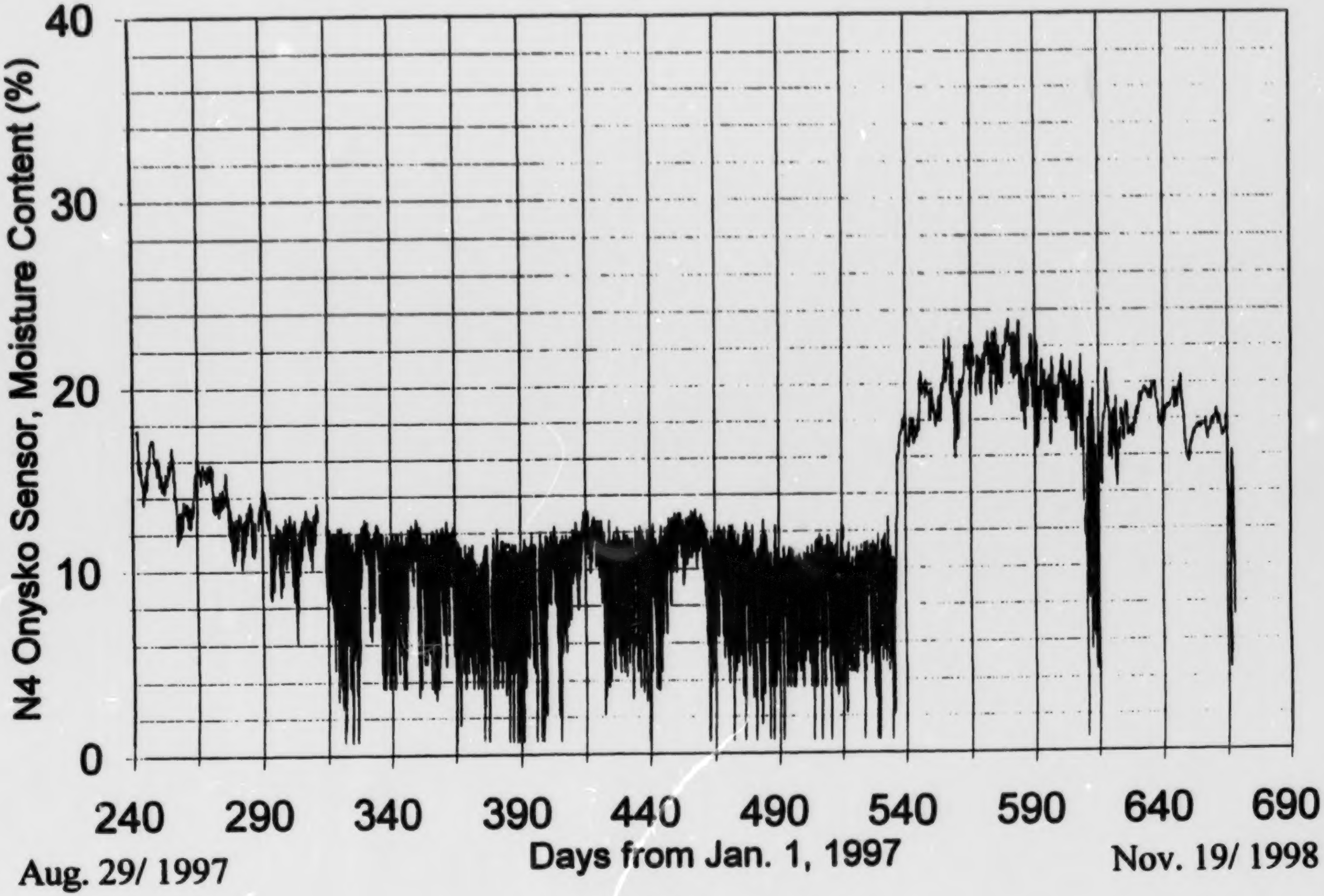


Figure 75. Onysko sensor moisture content at location N4.

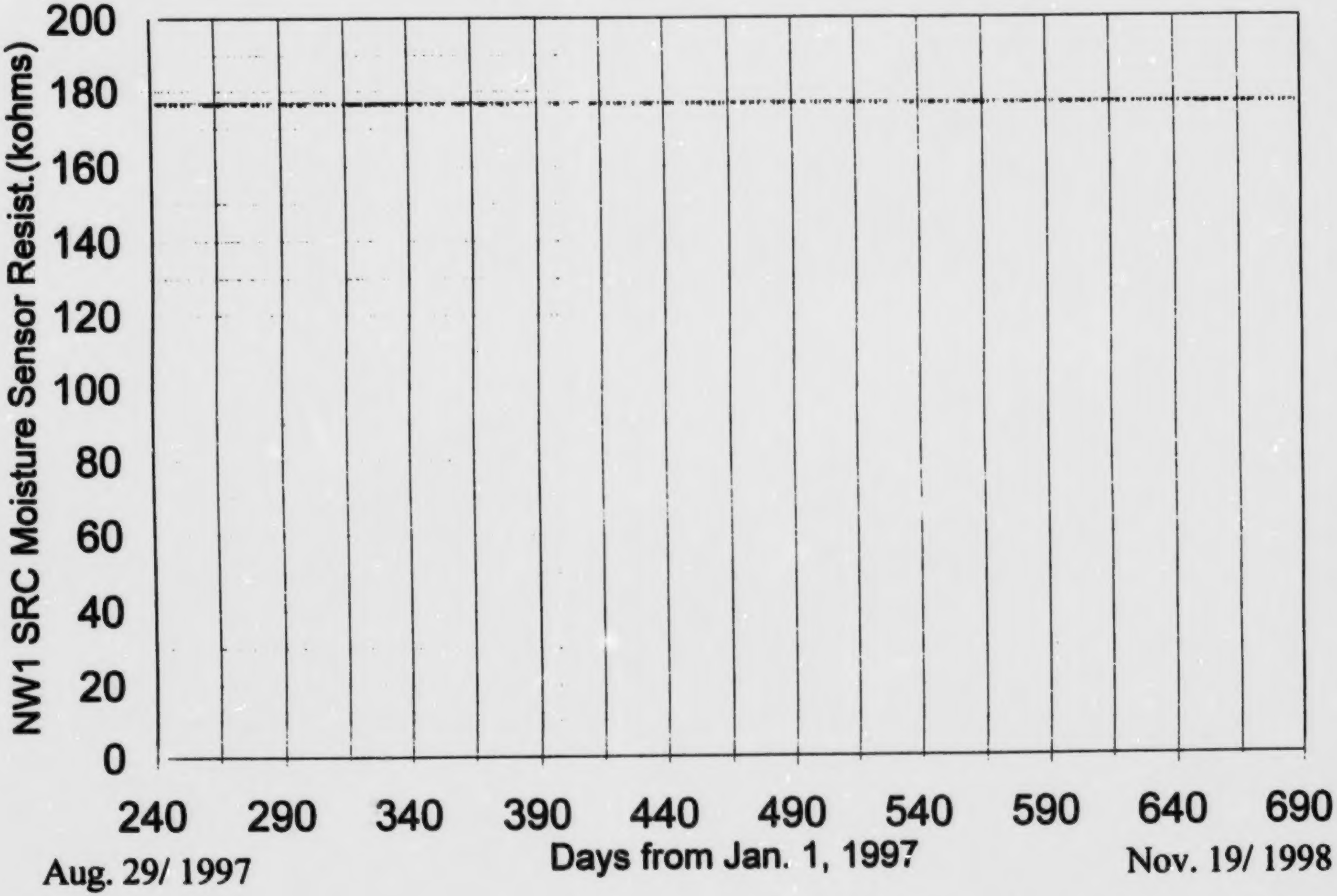


Figure 76. SRC moisture sensor resistance at location NW1.

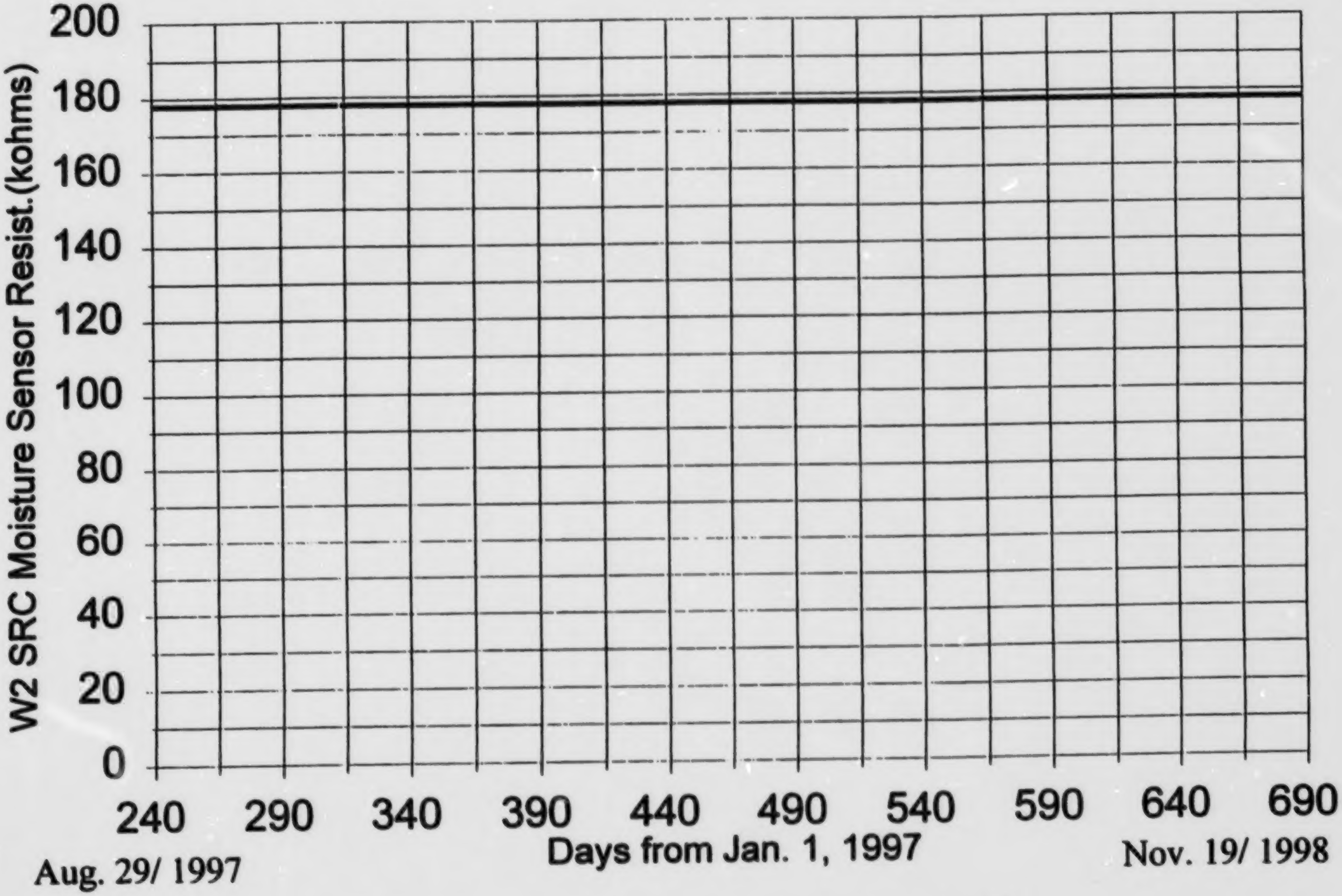


Figure 77. SRC moisture sensor resistance at location W2.

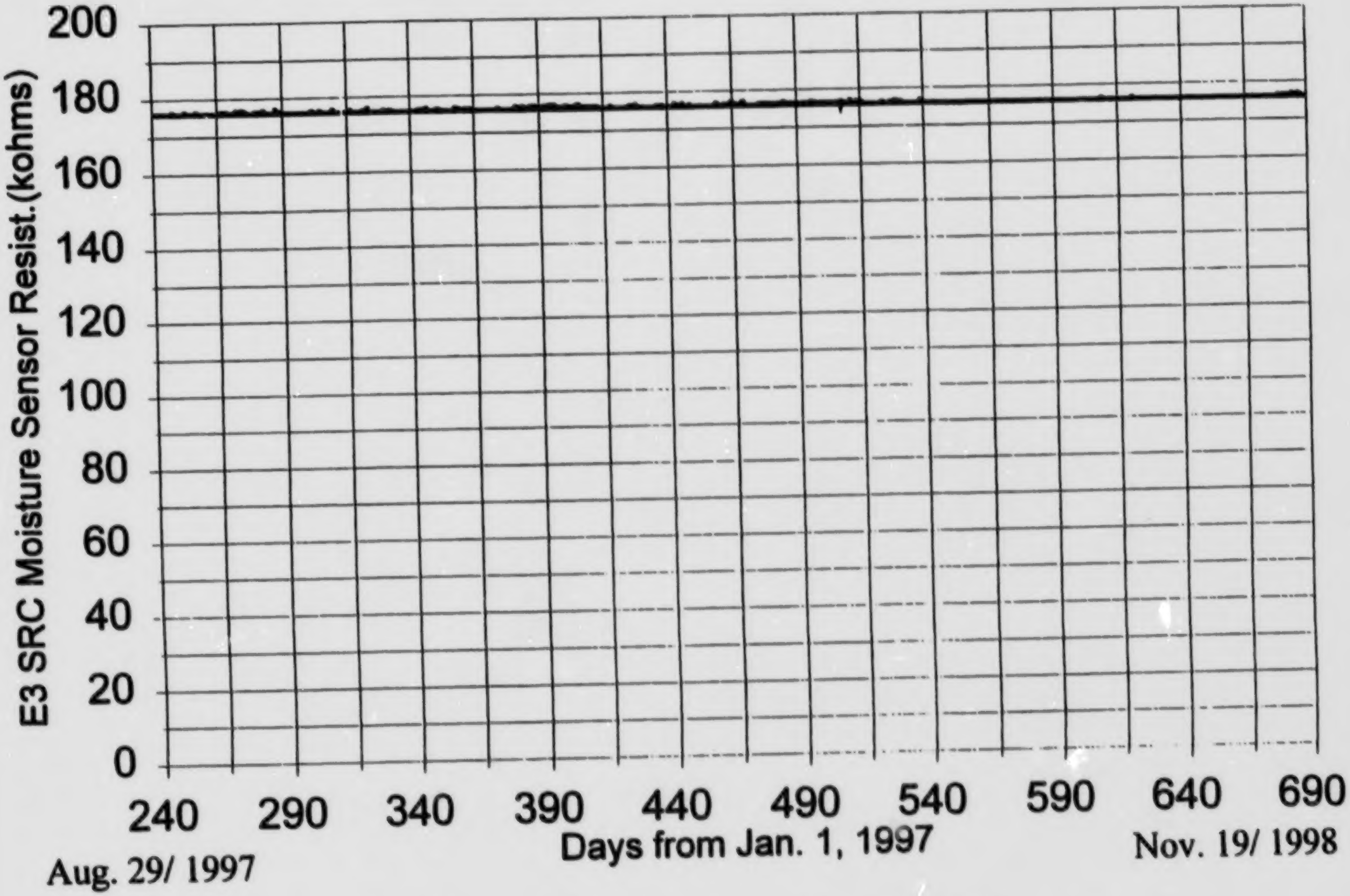


Figure 78. SRC moisture sensor resistance at location E3.

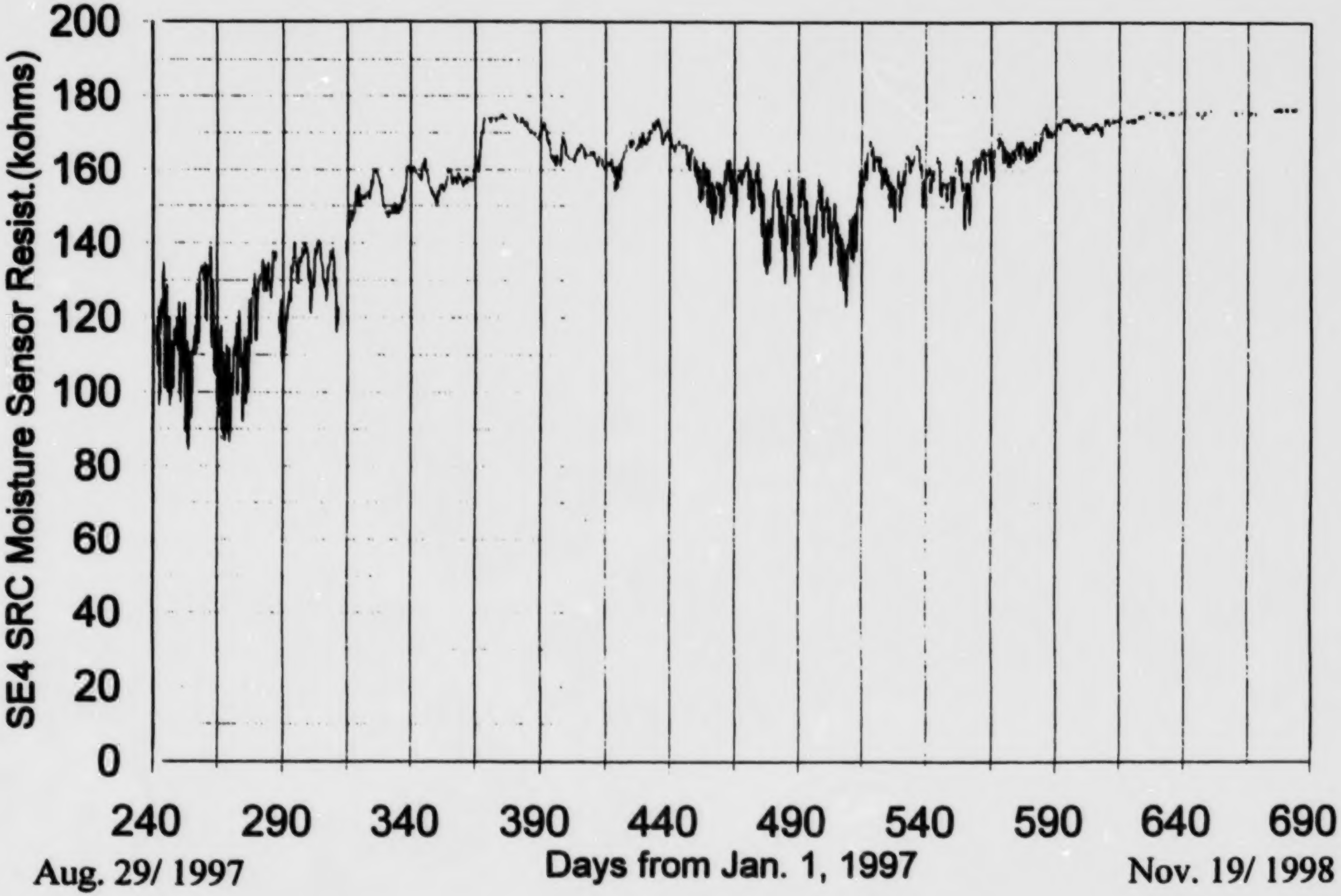


Figure 79. SRC moisture sensor resistance at location SE4.

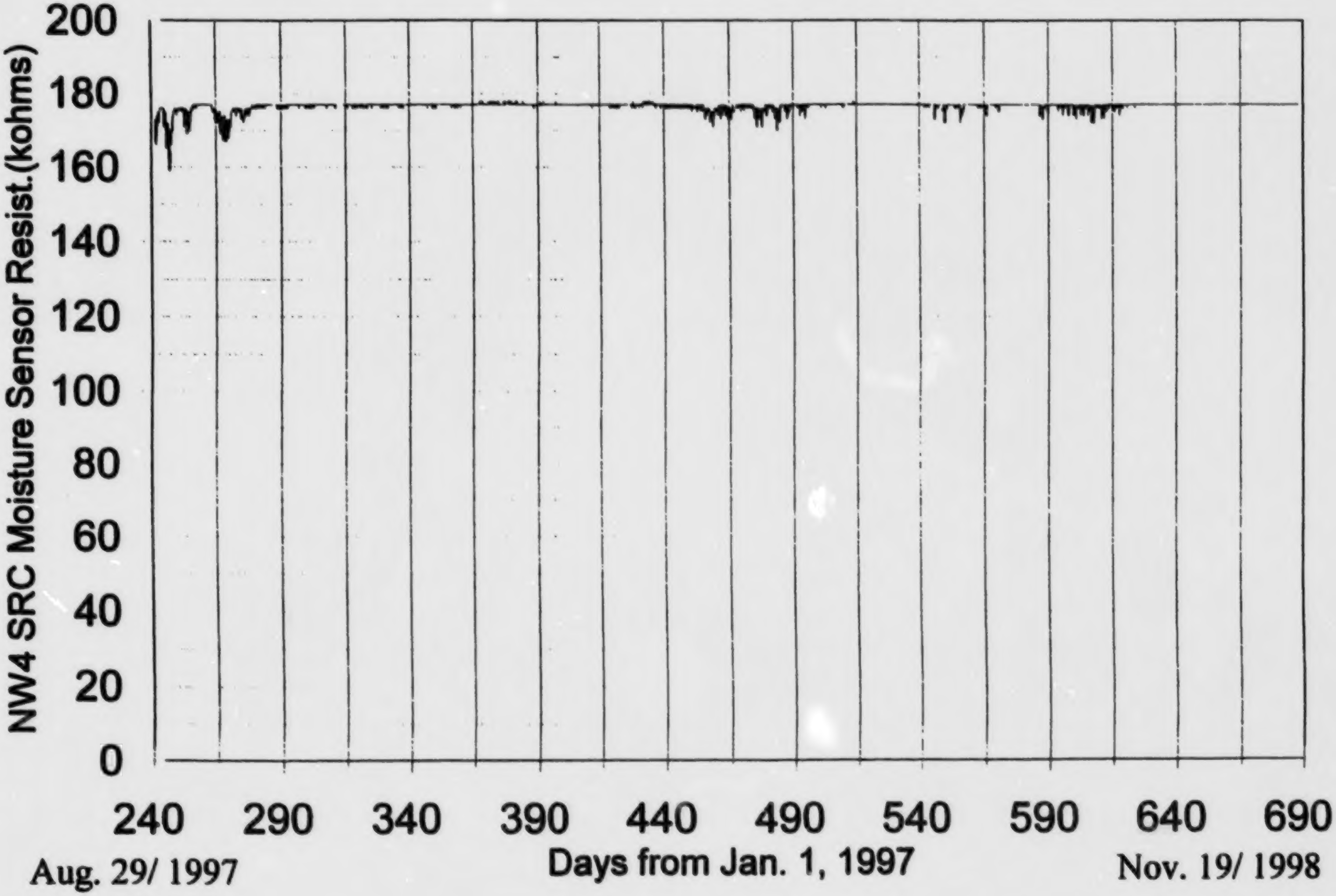


Figure 80. SRC moisture sensor resistance at location NW4.

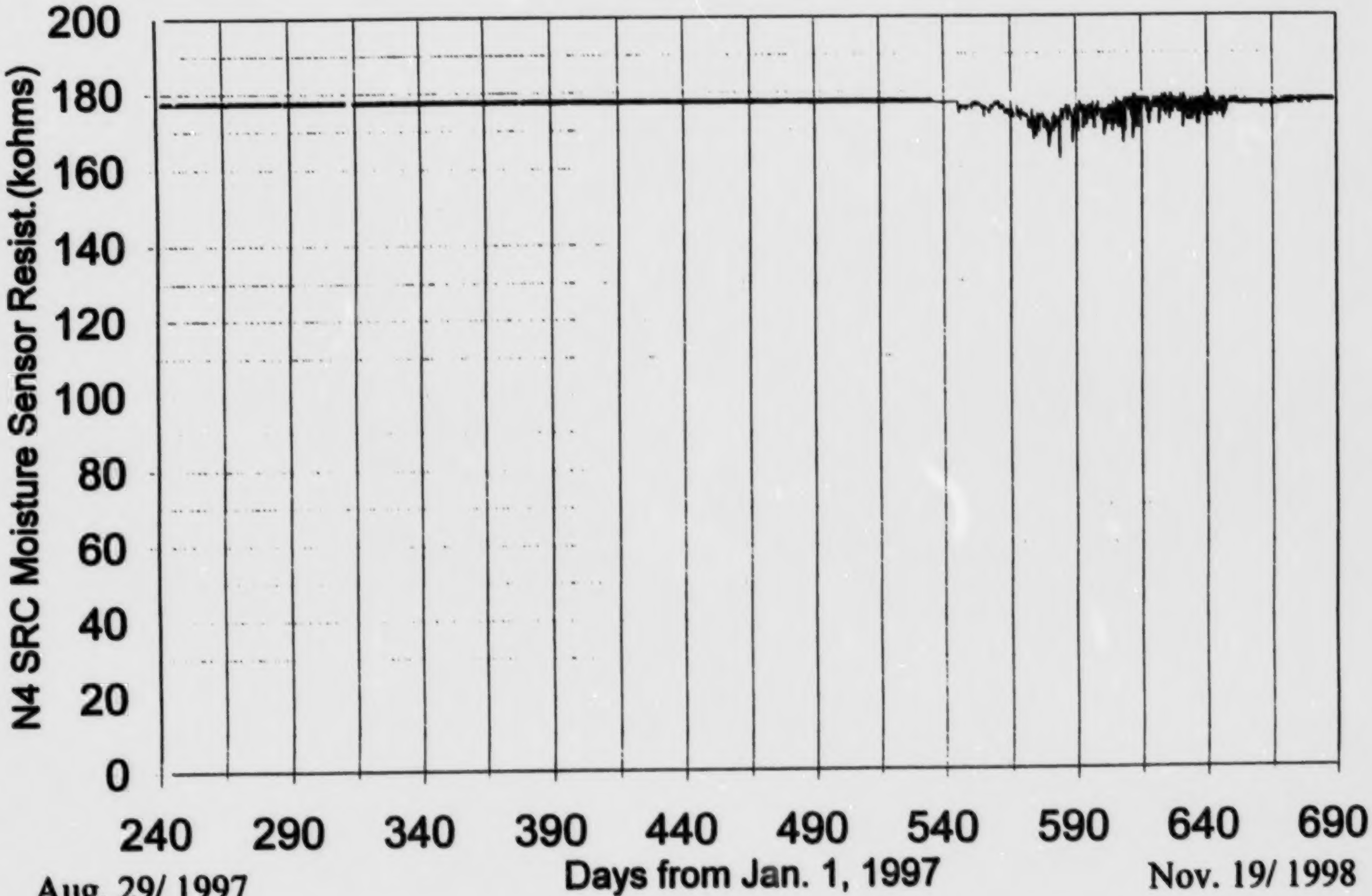


Figure 81. SRC moisture sensor resistance at location N4.

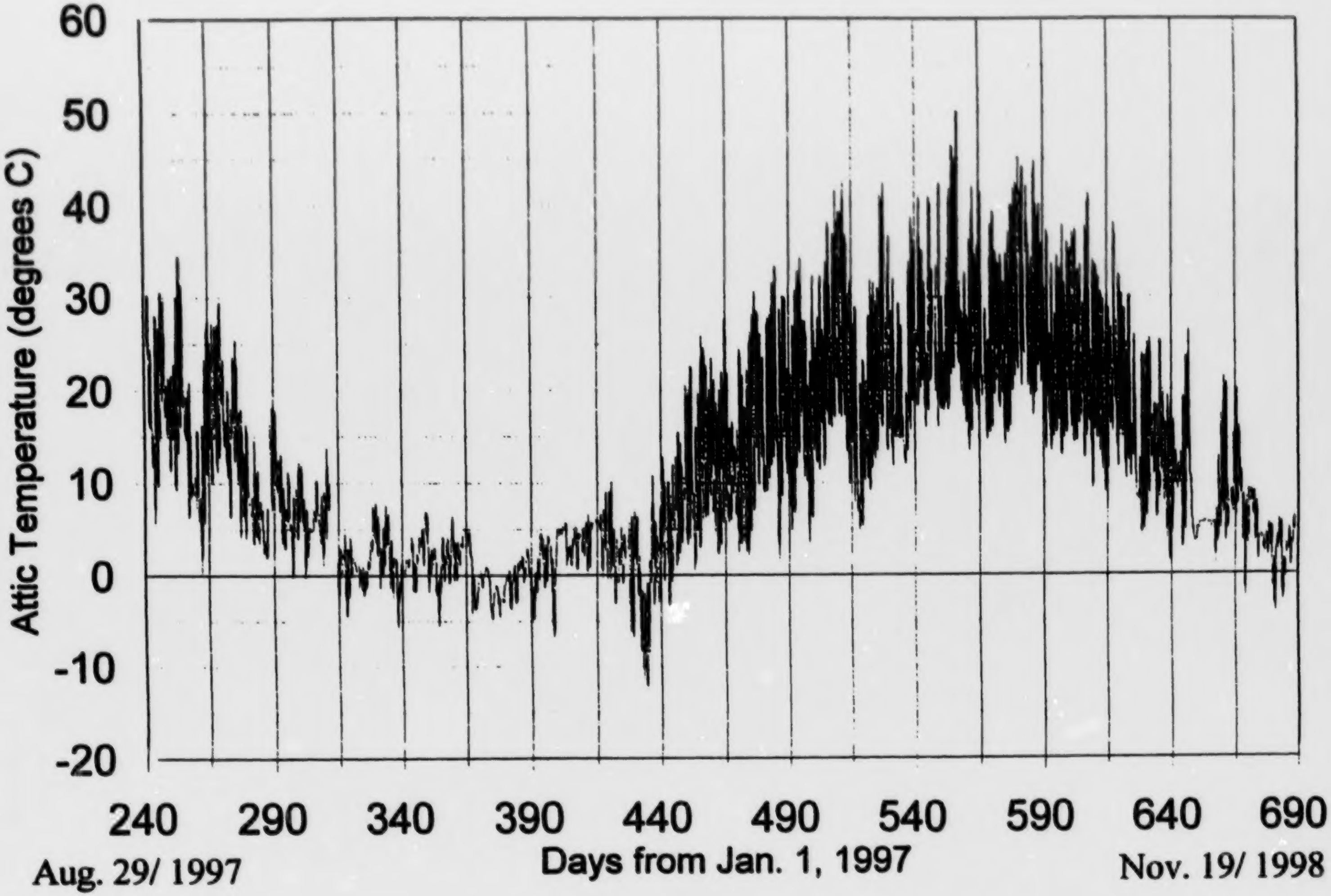


Figure 82. Attic temperature.

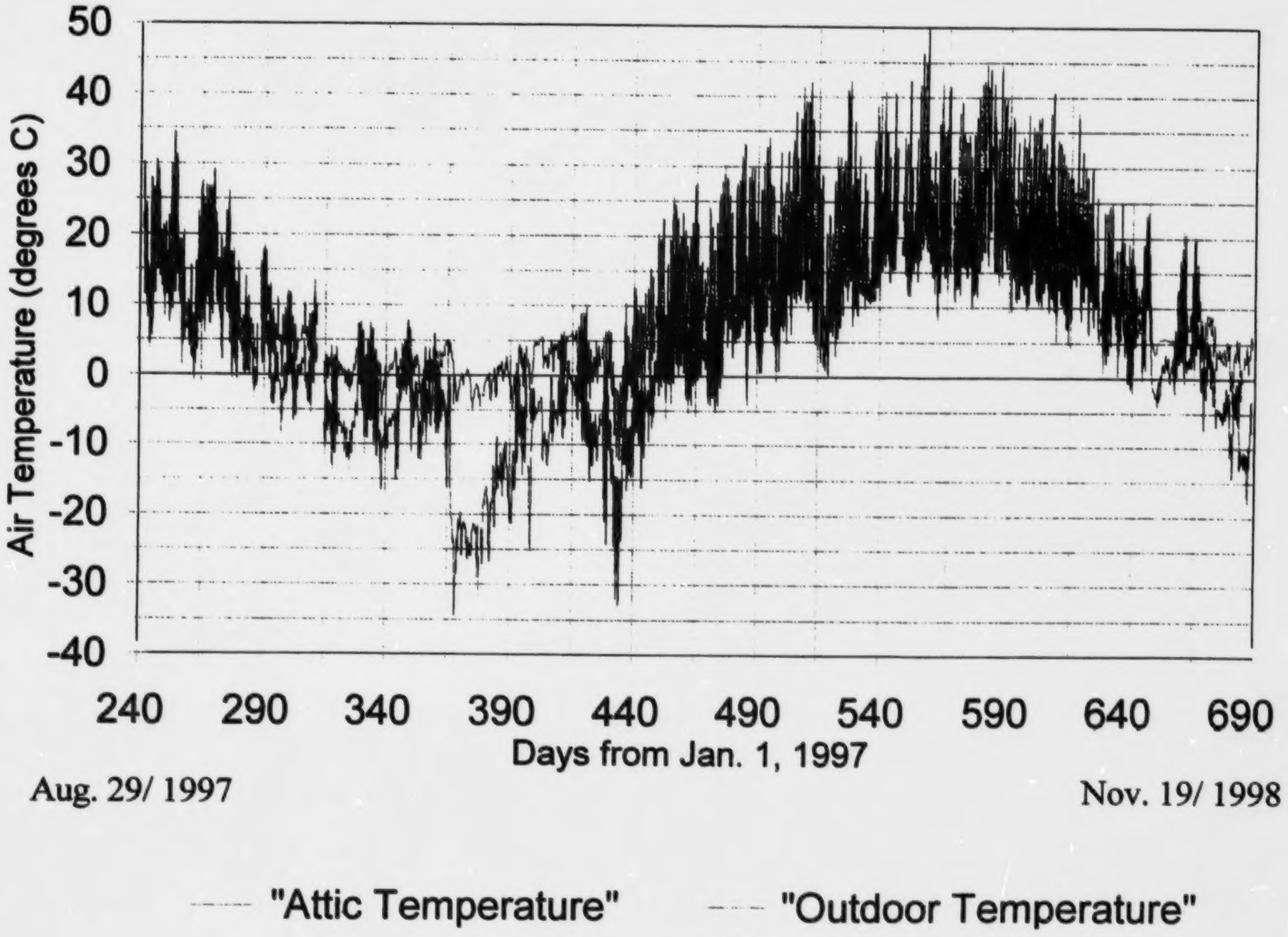


Figure 83. Attic temperature and outdoor temperature.

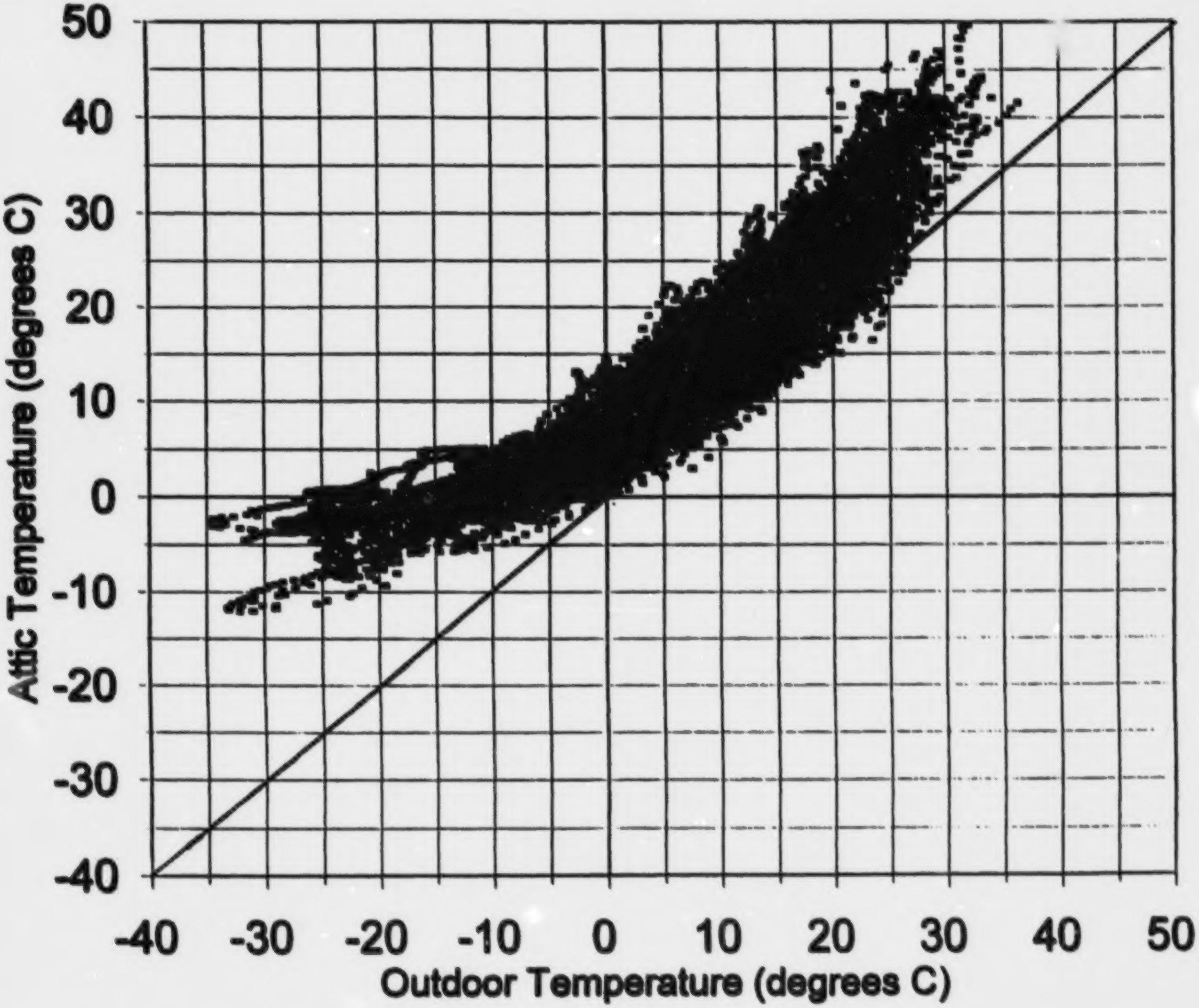


Figure 84. Attic temperature vs. Outdoor temperature.

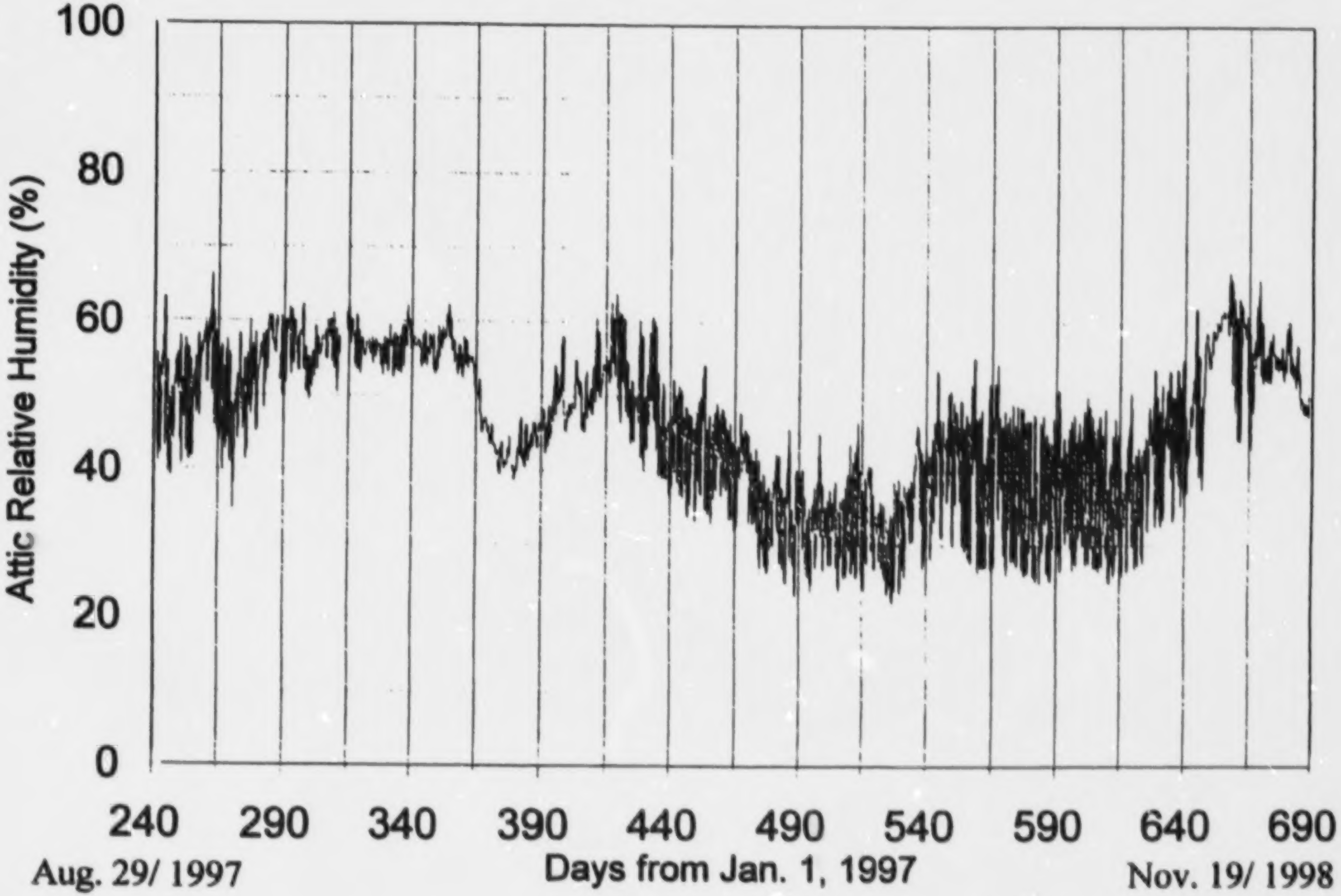
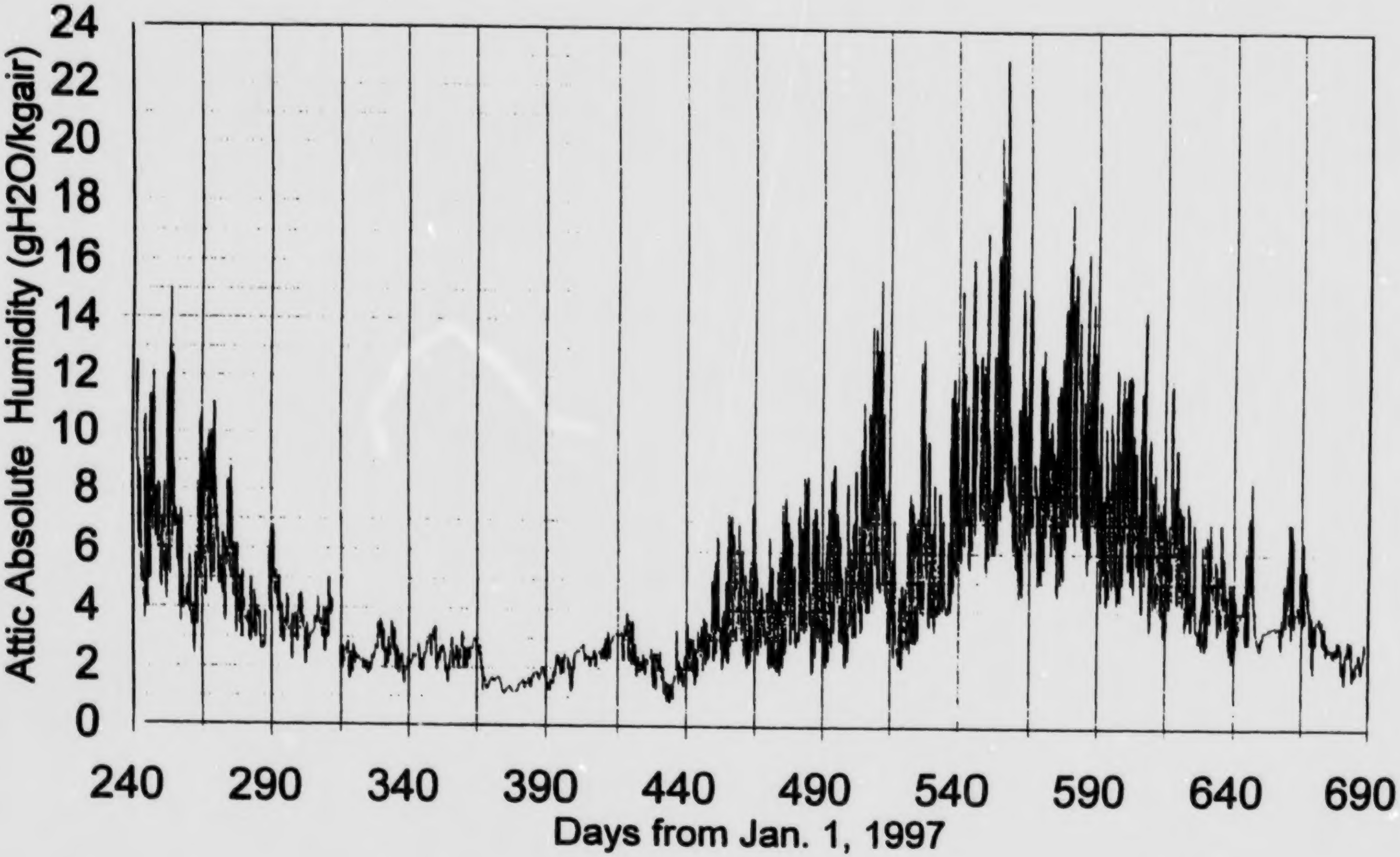


Figure 85. Attic relative humidity.



Aug. 29/ 1997

Nov. 19/ 1998

Figure 86. **Attic absolute humidity.**

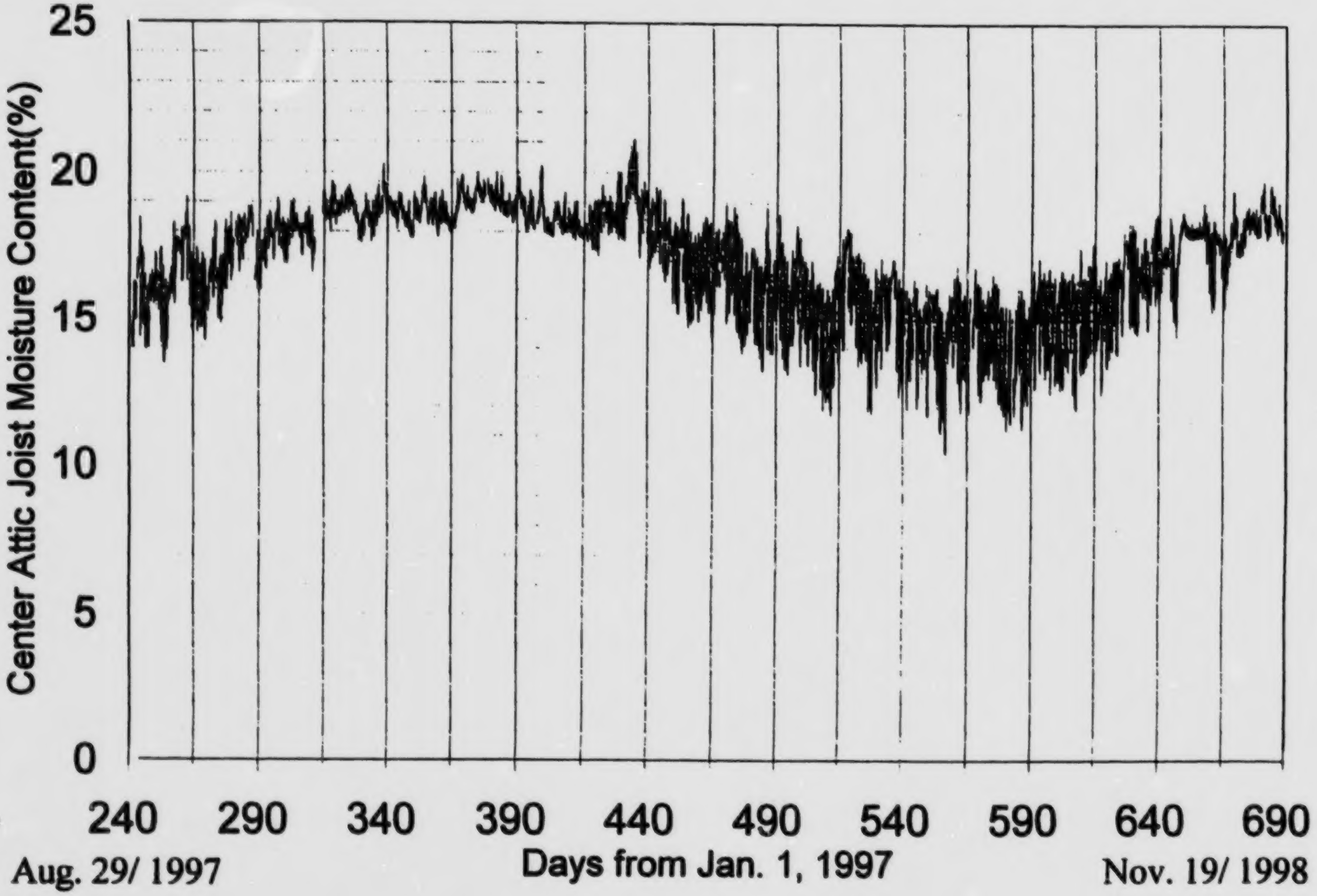


Figure 87. Center part of attic wood joist moisture content.

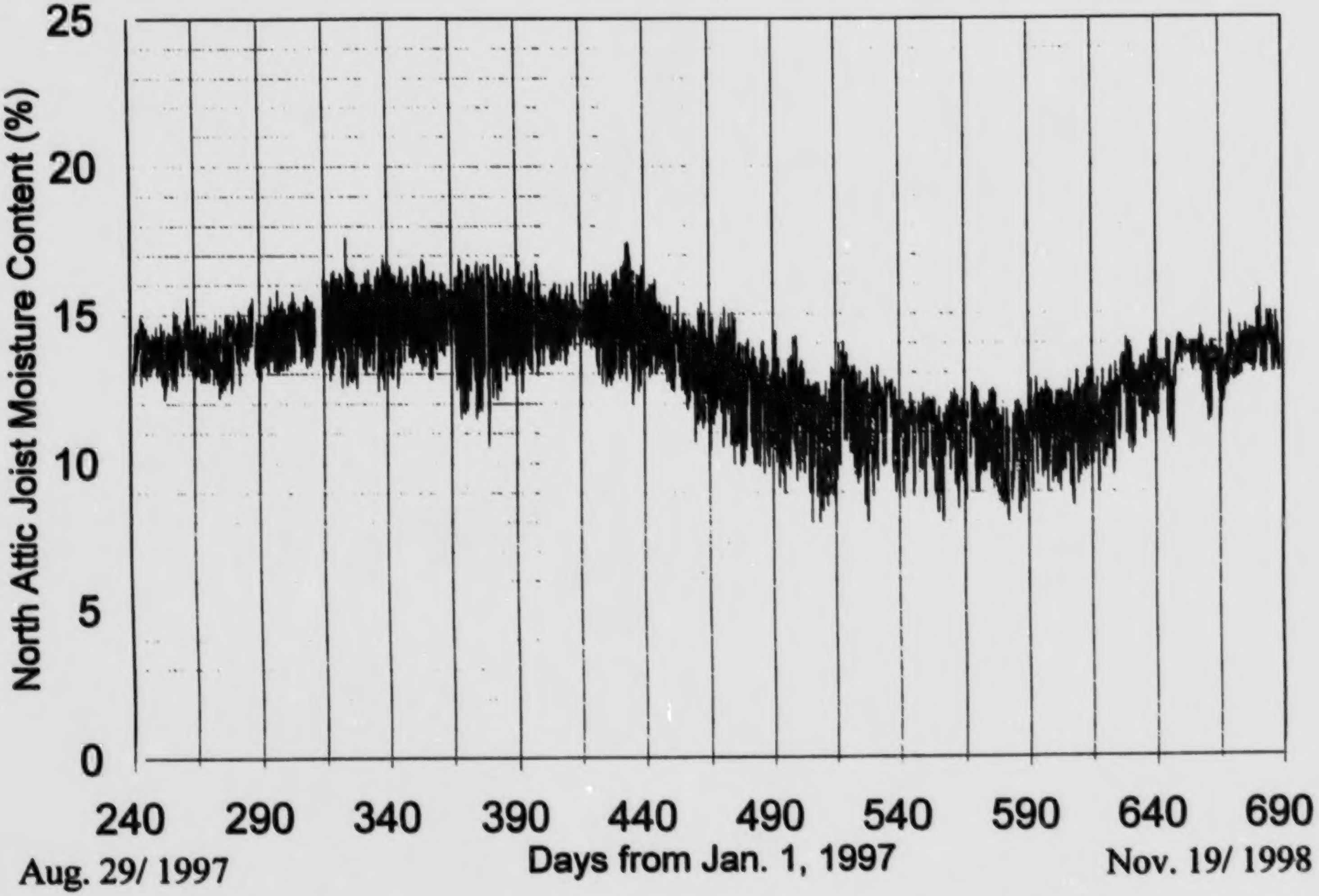


Figure 88. North part of attic wood joist moisture content.

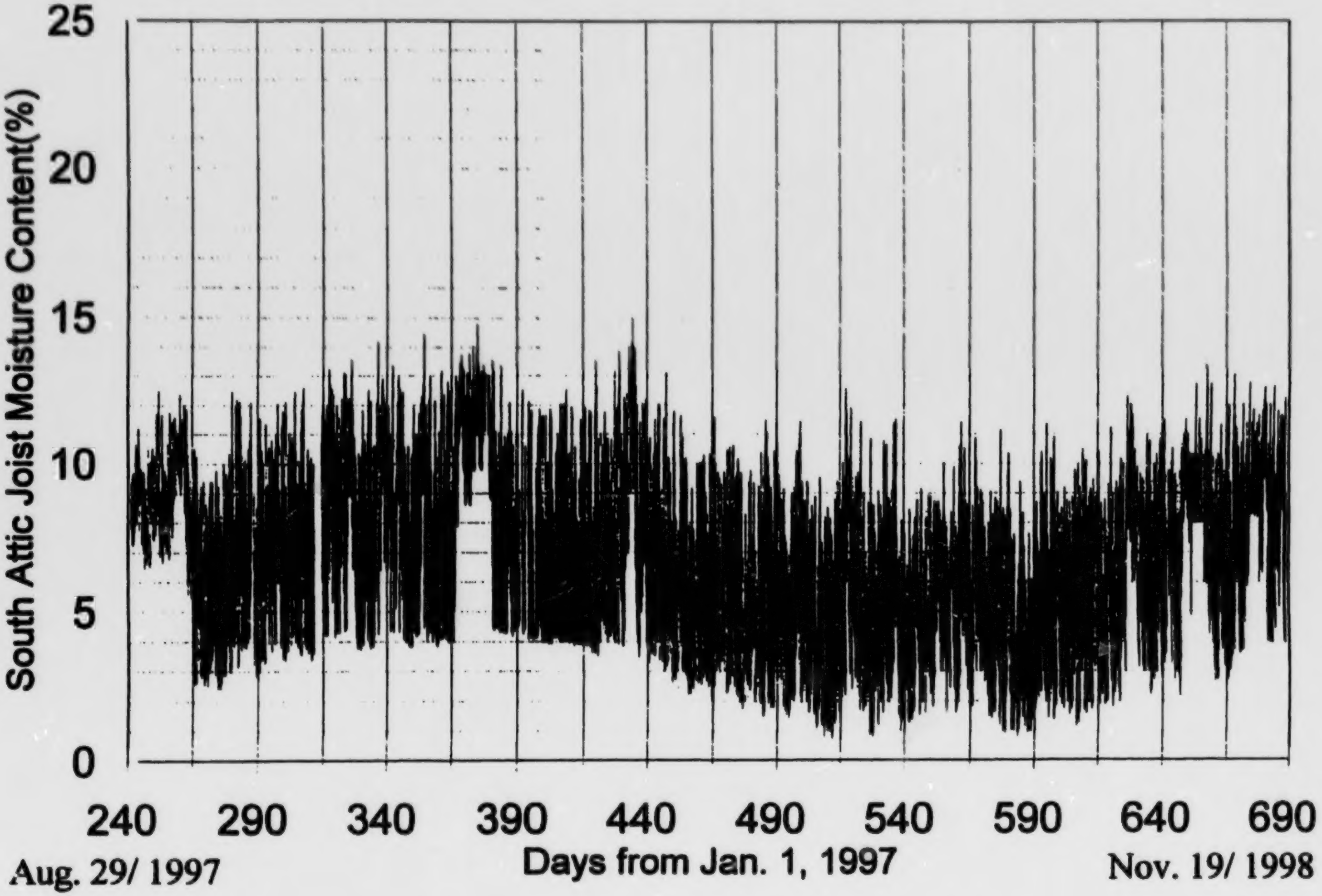


Figure 89. South part of attic wood joist moisture content.

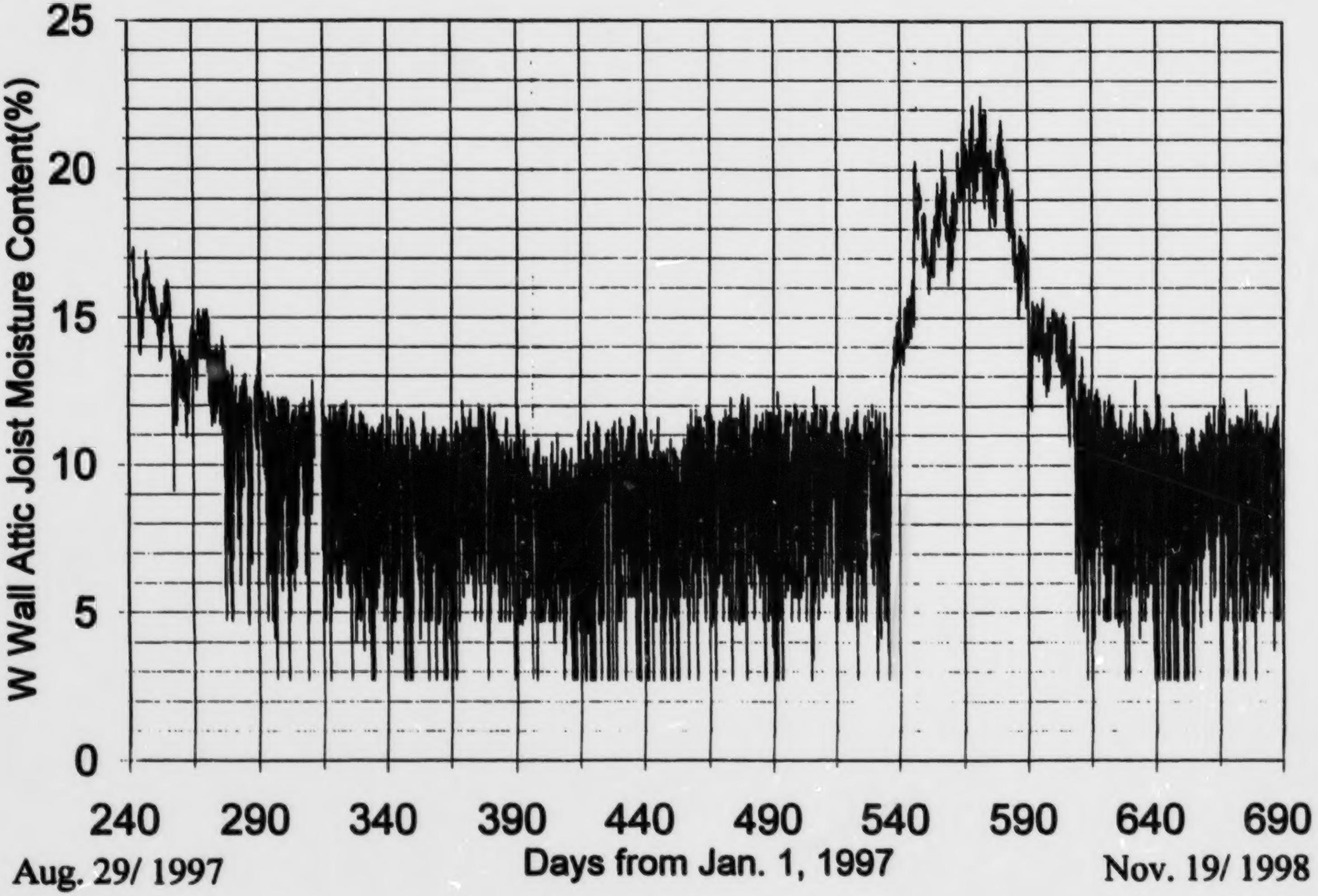


Figure 90. Moisture content of attic joist resting on north brick wall of building (West joist)

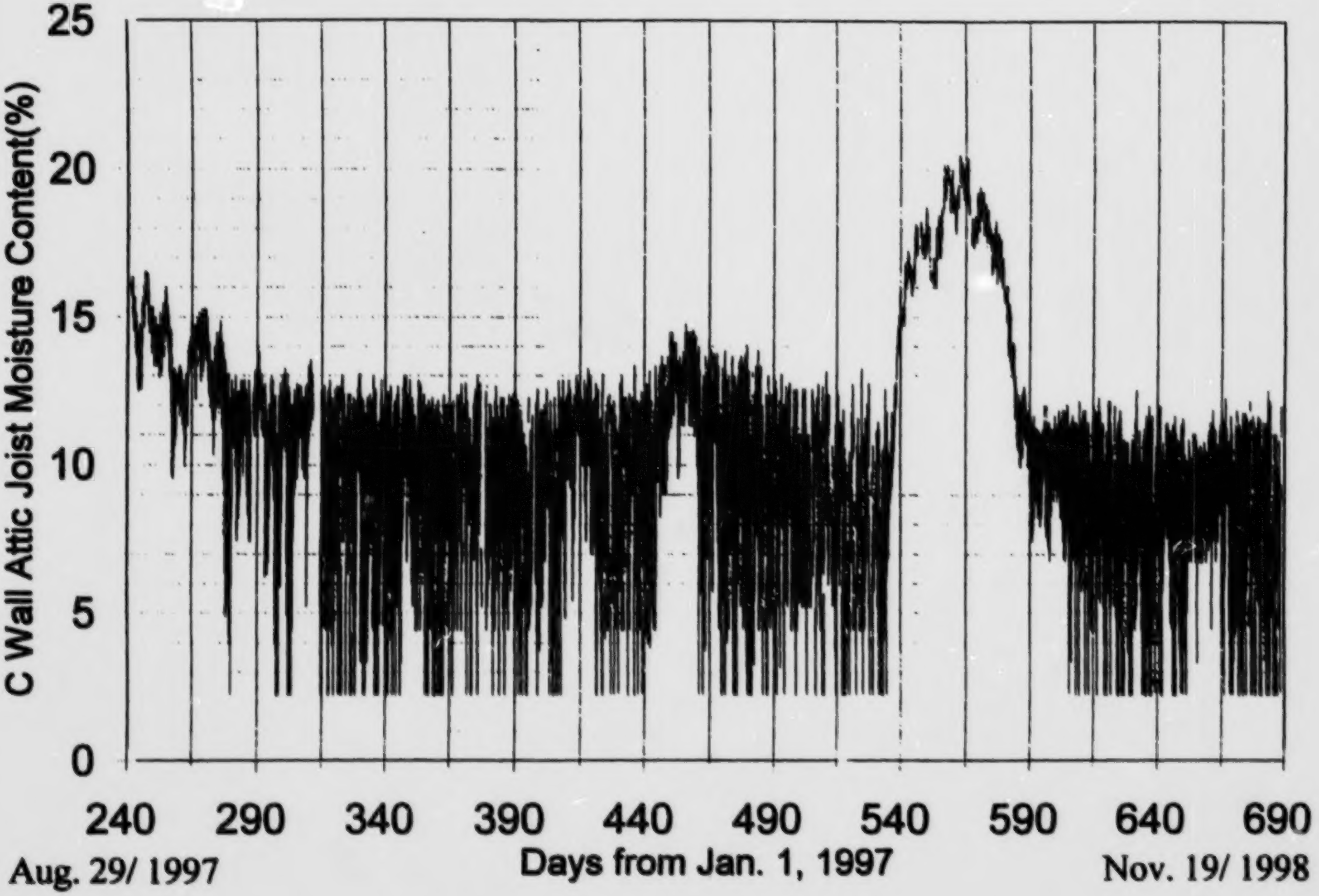


Figure 91. Moisture content of attic joist resting on north brick wall of building (Center joist)

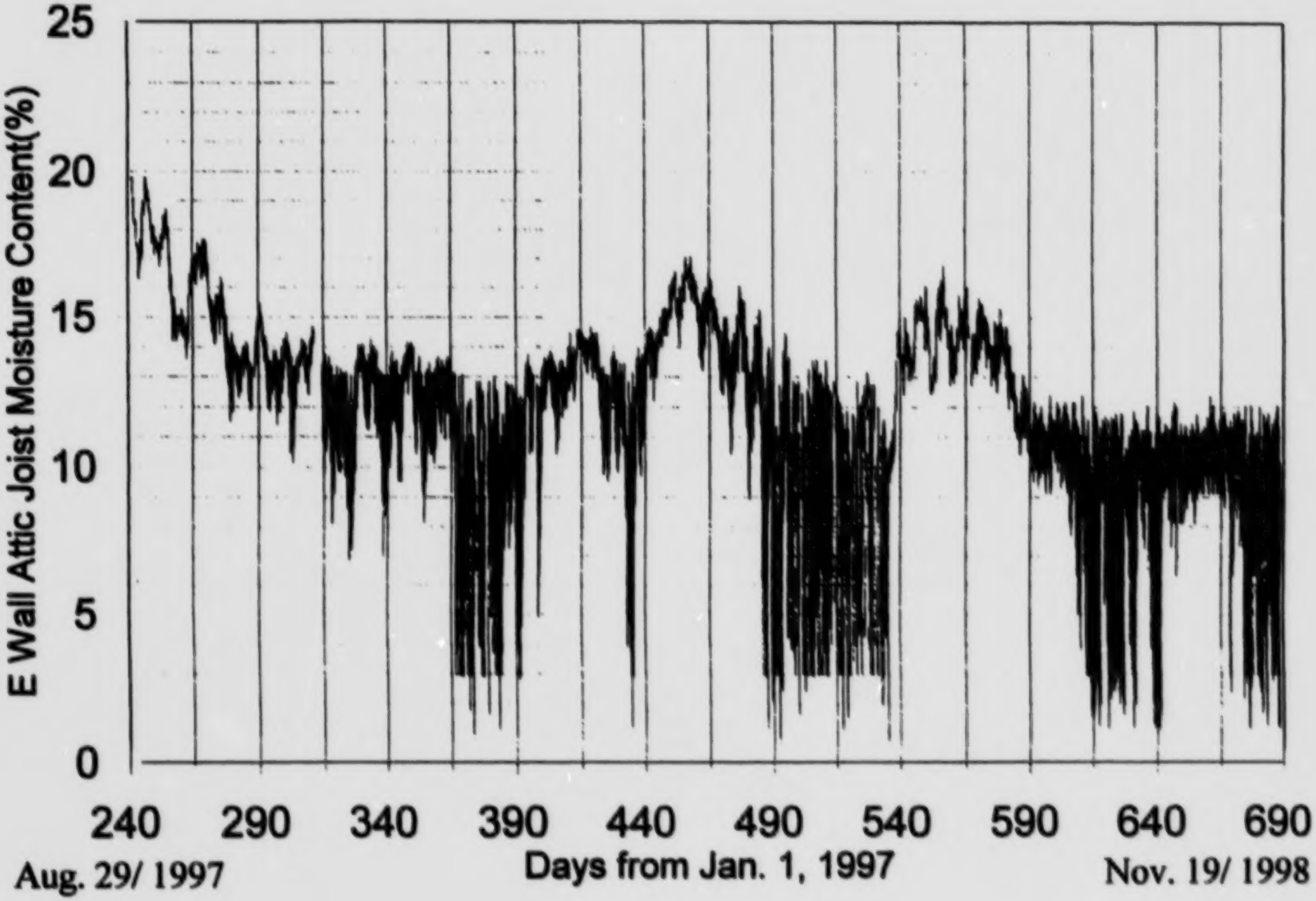


Figure 92. Moisture content of attic joist resting on north brick wall of building (East joist)

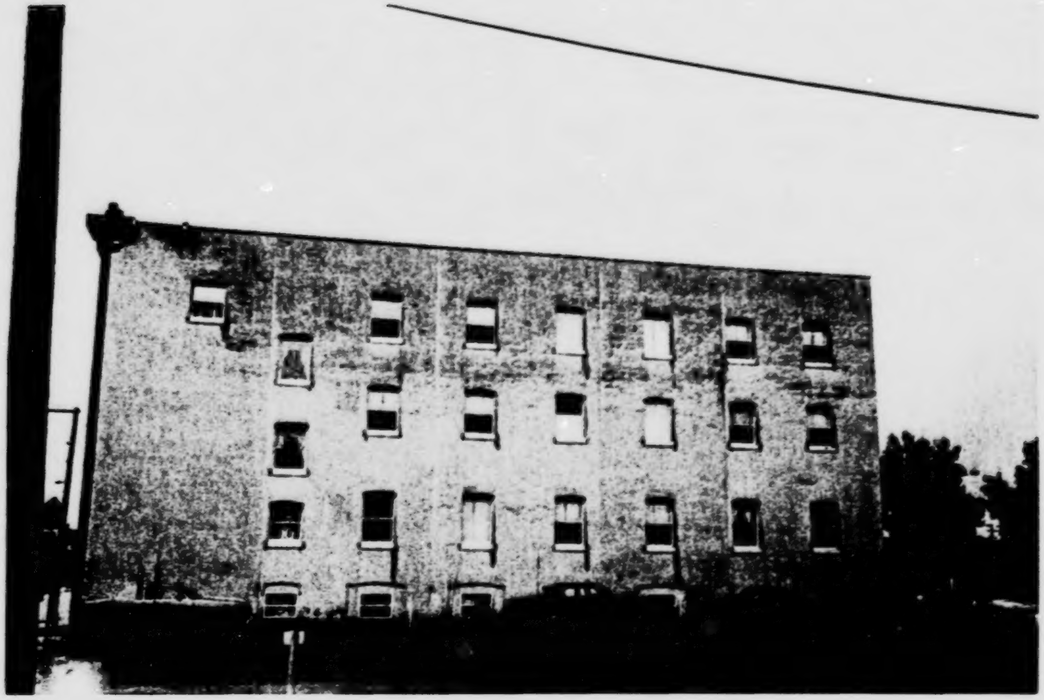


Figure 93. West side of the building following a rainstorm

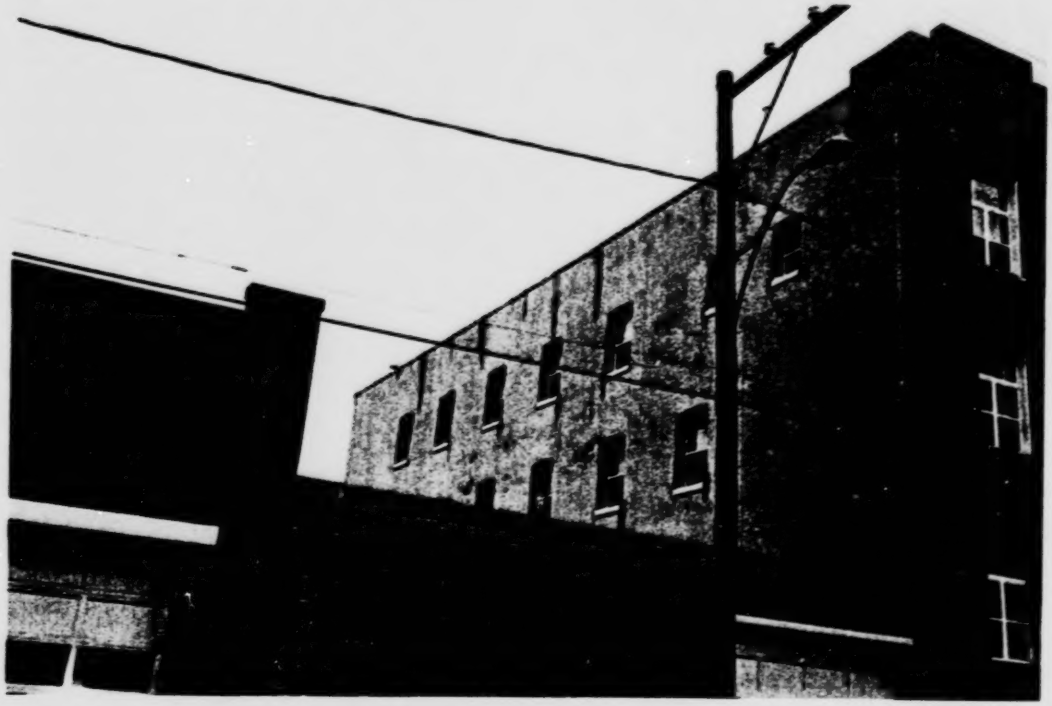


Figure 94. East side of the building following a rainstorm

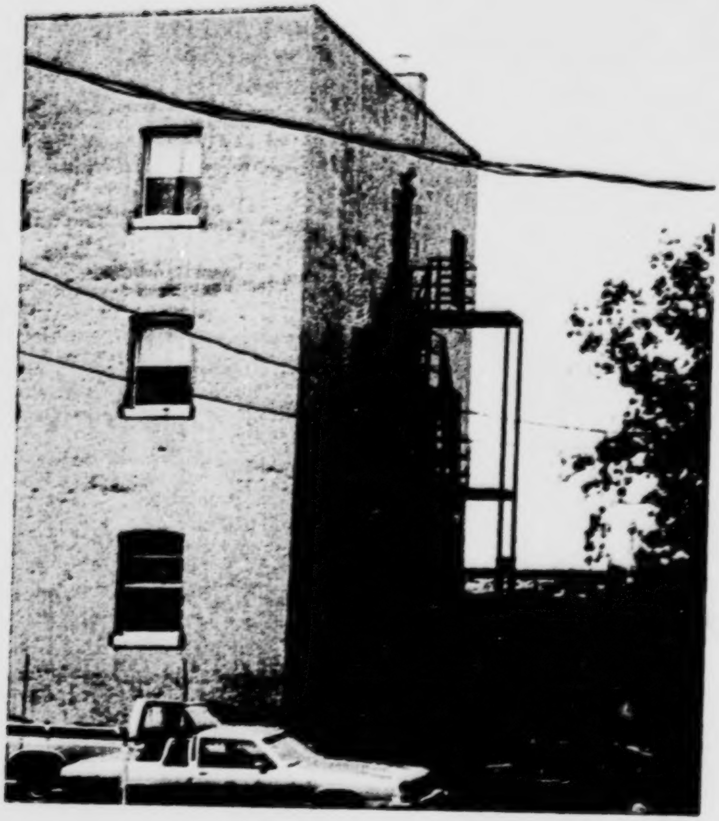


Figure 95. Southwest side of the building following a rainstorm

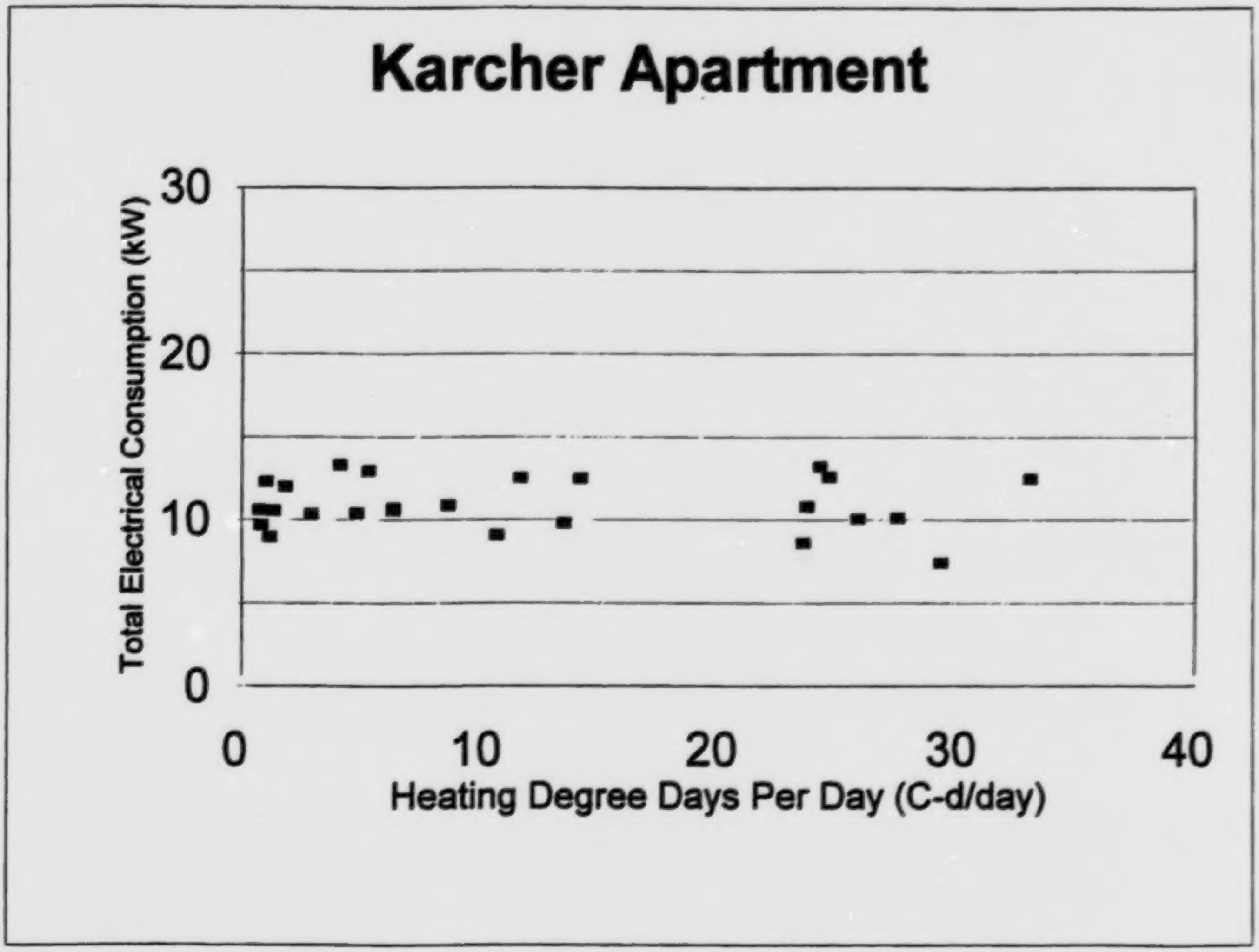


Figure 96. Total electrical consumption rate of building vs. heating degree-days/day.

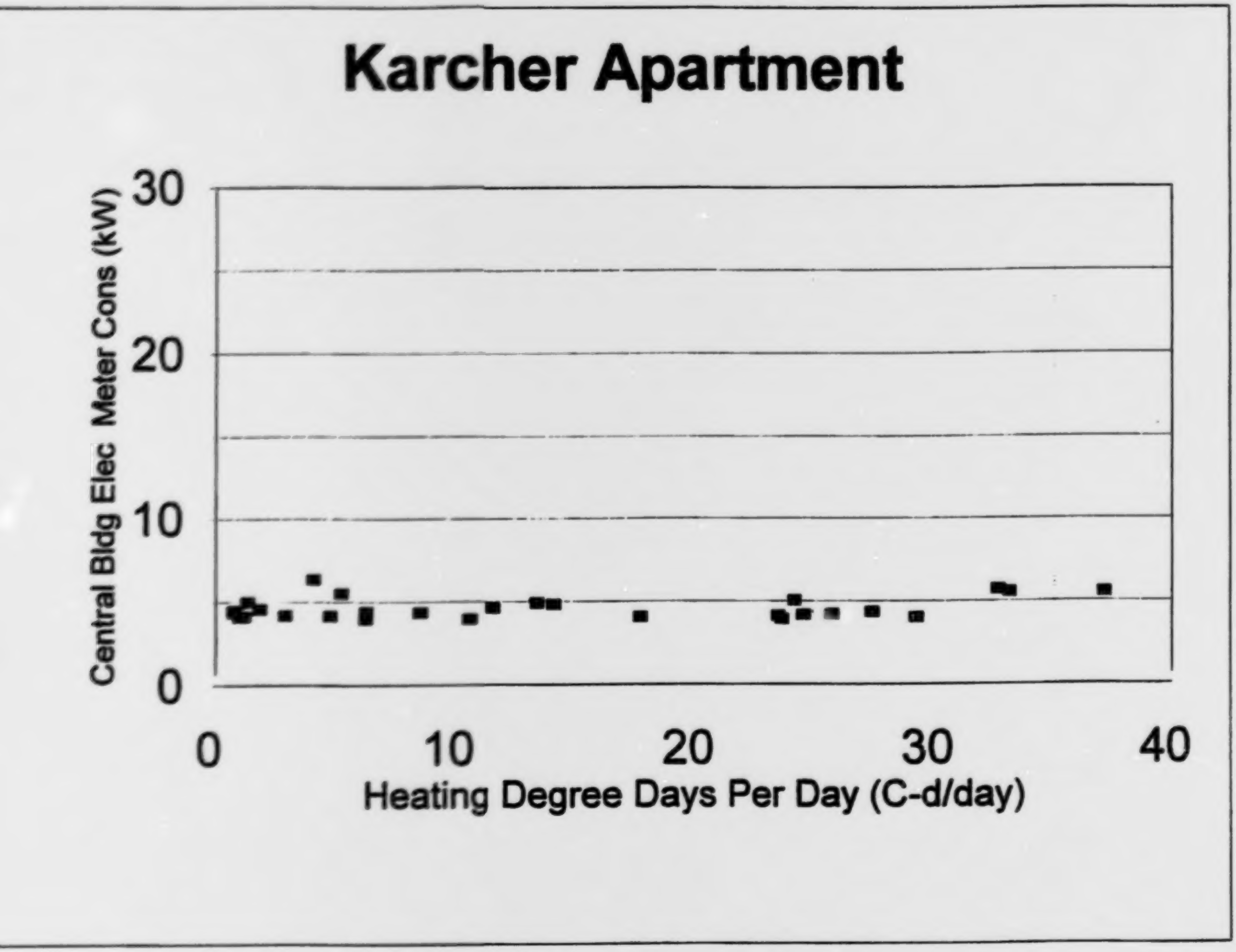


Figure 97. Common area electrical consumption rate of building vs heating degree-days/day.

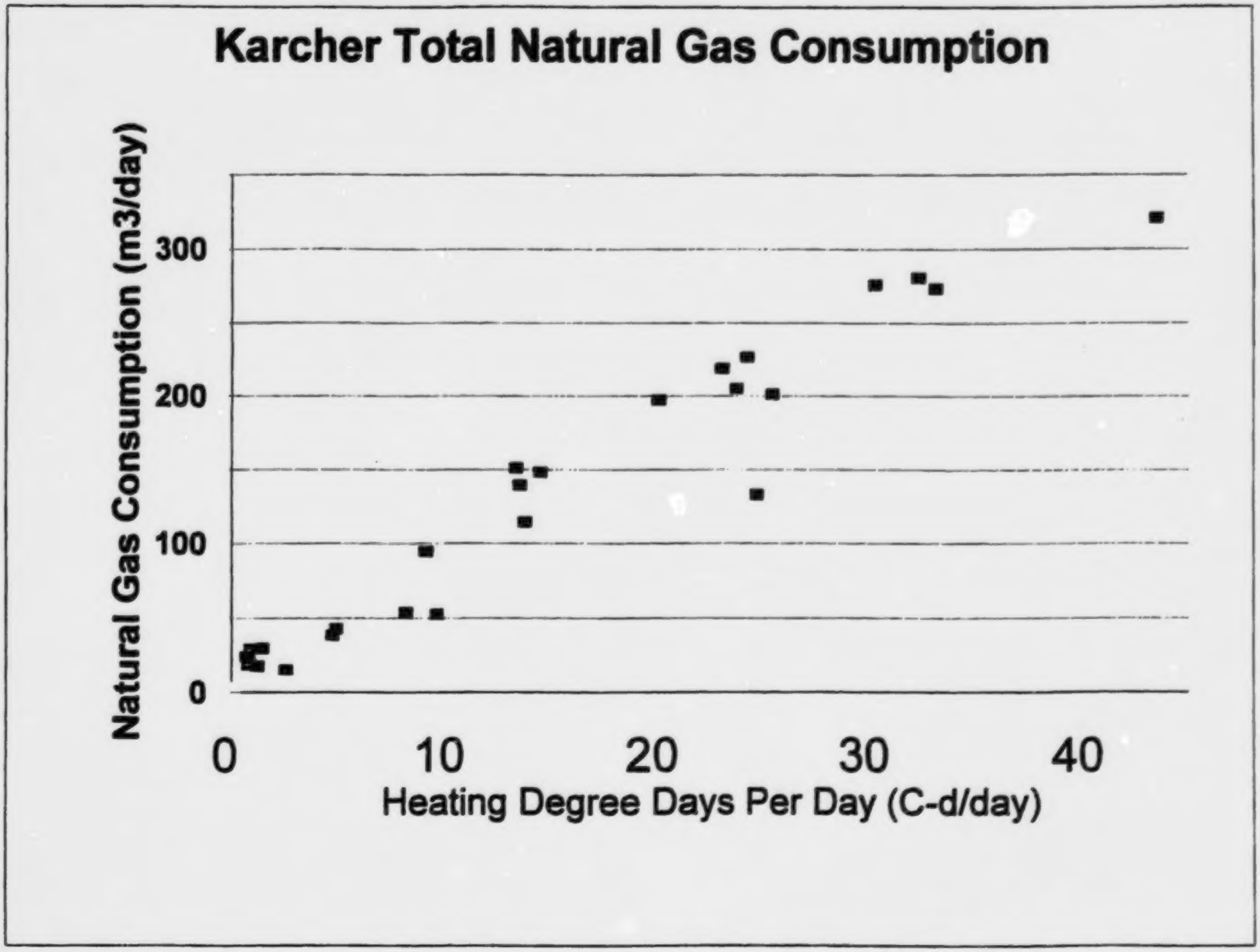


Figure 98. Total natural gas consumption vs. heating degree-days/day.

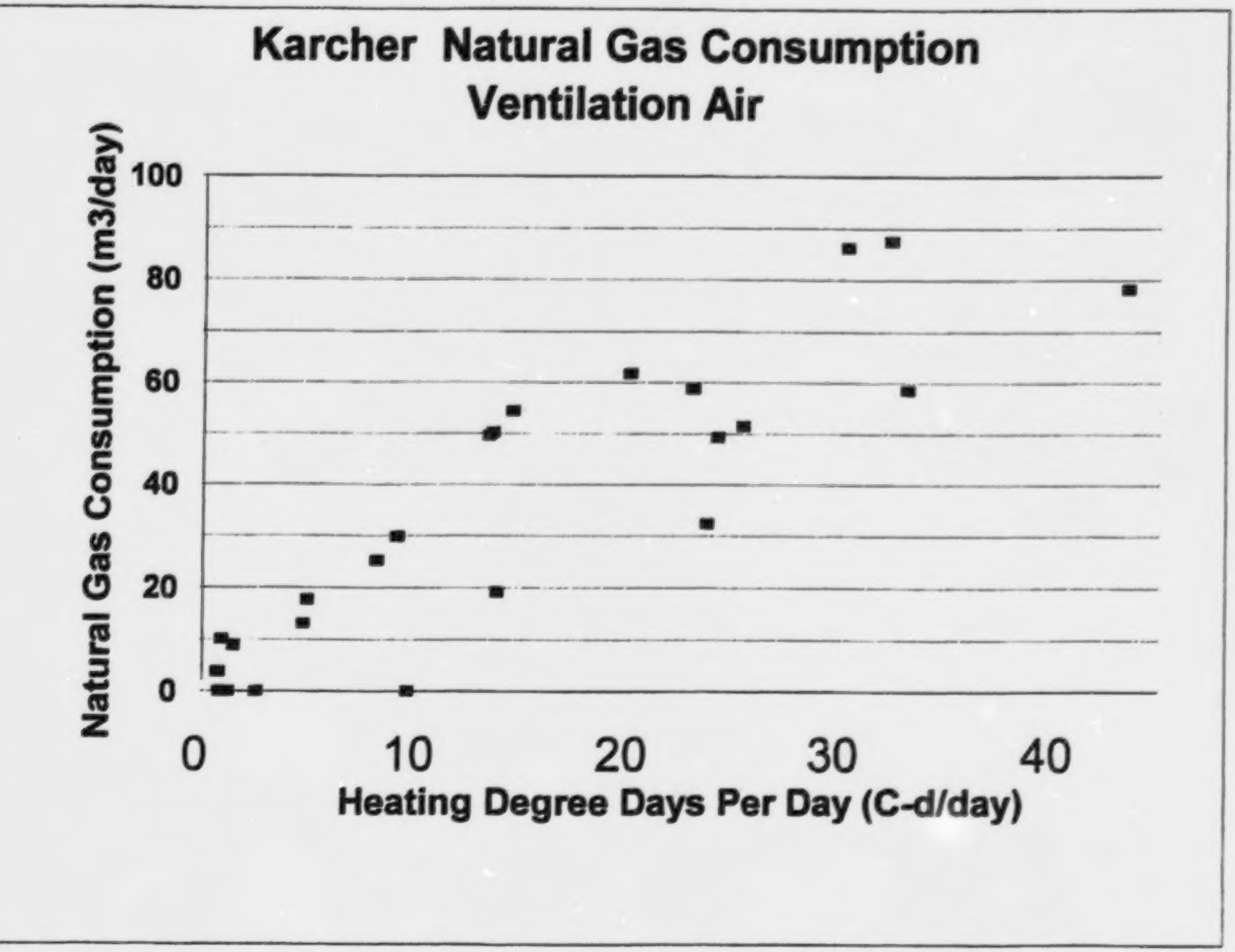


Figure 99. Natural gas consumption for ventilation boiler vs. heating degree-days/day.

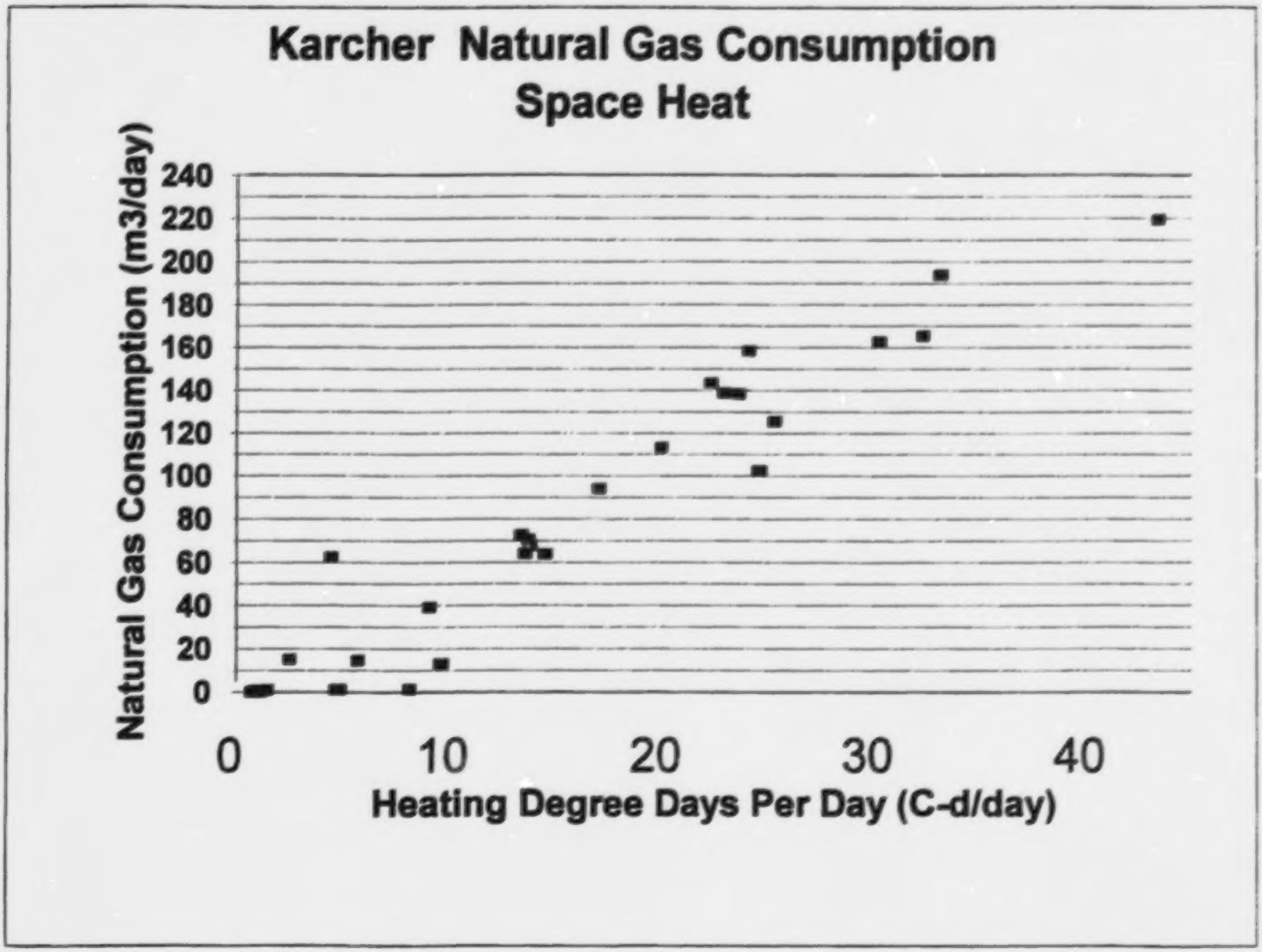


Figure 100. Natural gas consumption for space heating boilers vs. heating degree-days/day.

Appendix 1

Interim Reports on the Project

INTERIM REPORT #1

The Renovation of an Apartment Building with Solid Masonry Walls

Pre-retrofit conditions and technical input to the construction process

for

Canada Mortgage and Housing Corporation
Ottawa, ON

by

Building Performance Section
Saskatchewan Research Council

Small Industry Support Branch

SRC Publication No. I-4800-9-C-97

March, 1997

Day Number (Jan 1, 1997=1)	Month	Monthly Rainfall (mm)	Monthly Snow (cm)	Total Precipitation (mm)
213-243	August 1997	80.4	0	80.4
244-273	September	42.9	0	42.9
274-304	October	31.3	3.0	34.3
305-334	November	7.6	2.2	9.2
335-365	December	0.8	12.9	10.8
366-396	January 1998	0	36.2	32.8
397-424	February	2.5	8.6	9.2
425-455	March	0.2	10.1	9.7
456-485	April	15.2	Trace	15.2
486-516	May	5.0	0	5.0
517-546	June	120.5	Trace	120.5
547-577	July	50.1	0	50.1
578-608	August	27.8	0	27.8
609-638	September	26.8	0	26.8
639-669	October	28.6	56.4	84.0
670-699	November	3.6	4.6	6.4

During the month of June 1998, Prince Albert received 120.5 mm of rain, which is almost double the long term average of 66.9 mm.

Because of the importance of rainfall to the building envelope moisture performance, a plot was made of the monthly rainfall values during the monitoring period, along with the long term average rainfall. This data is plotted in Figure 20. The very high rainfall in Prince Albert in June 1998 is evident from the graph. Prince Albert is located in a relatively dry area. Typical long term average annual precipitation is equal to 405.6 mm, according to Environment Canada data.

2.2 Interior Conditions

A plot of the exhaust air temperature measured in the exhaust air duct in the hallway of the second floor of the building is presented in Figure 21. A minimum temperature of 15.5°C was reached on Day 463 (April 8, 1998). At this time, the boiler had been turned off for a short period of time. The peak temperature measured was approximately 32°C on Day 585 (August 8, 1998). There is no air conditioning in the building and thus high interior temperatures are possible in the building in the summer. The building has a long axis facing west which contributes to afternoon solar gains. The untempered outdoor air supply to the building also adds to the heat transfer from outdoors to the inside during the summer period.

There are individual suite thermostats which control the heat output from the radiant floor heating during the heating season. As can be seen from Figure 21, the average indoor air temperature is relatively high for the building, with many days during the heating season exceeding 25°C. According to the building owner, who owns a number of apartment buildings, this relatively high indoor temperature is caused by the apartment dwellers' preferred temperature, and is not a control problem with the heating system. The average indoor temperatures for the four seasons of the year are presented in the following table.

Table 2. Measured Interior Temperatures at the 2nd Floor Exhaust Duct

Season		Indoor Temperature °C
Fall 1997	Sept 21-Dec 21	24.7
Winter 97-98	Dec 21-March 21	24.3
Spring 98	March 21-June 21	24.9
Summer 98	June 21-Sept21	26.1

The relatively high indoor temperatures during the heating season contribute to increased heat loss from the building. The higher temperatures also lower the indoor relative humidity slightly. The midpoint temperature of the ASHRAE Winter Comfort Zone during primarily sedentary activity is approximately 22.3°C, at a relative humidity of 30%, with a low temperature in the comfort zone of 20.5°C and a high temperature of 24.3°C. Thus the temperature in the building is at the high end of the ASHRAE Winter Comfort Zone.

The relative humidity of the air in the exhaust duct on the second floor is plotted in Figure 22. From season to season the relative humidity indoors changes greatly. The relative humidity indoors at the start of the monitoring period reached a peak in early September 1997 of 46% falling to about 4% at Day 390 (January 25, 1998). There is no humidification on the central make-up air for the building, and, according to the on-site custodian, none of the apartment dwellers use individual room humidifiers. In the summer period around Day 560 (July 14, 1998) the peak interior humidity reached a value of about 58%.

The Canadian guidelines for indoor relative humidity are as follows:

30% to 80% relative humidity – Summer
20% to 55% relative humidity - Winter*
* unless constrained by window condensation

During the summer period of 1998, the relative humidity in the building met the Canadian guideline, as the relative humidity did not exceed 58%, and the average humidity was above 30% for most of the summer period. In the other three seasons, however, the average humidity values were well below 30%, as can be seen from Figure 22. The relatively high continuous ventilation rates, the low outdoor air absolute humidity values, and the absence of humidification in the building are the causes of the low indoor humidity.

The absolute humidity in the exhaust air duct was calculated using the measured temperature and measured relative humidity. This plot is presented in Figure 23. The shape of this plot tends to mimic that of the exhaust air relative humidity shown on the previous graph (Figure 22), as the interior temperature inside the building is relatively constant. The lowest value of absolute humidity in the building was reached around Day 390 (January 25, 1998) at 0.75 grams of water per kilogram of air. The peak absolute humidity indoors reached in the summer period at Day 560 (July 14, 1998) was 15.6 grams of water per kilogram of dry air. This value is close to the maximum absolute humidity of 16 grams of water per kilogram of dry air measured outdoors on the same day.

2.3 Wall Temperature Profiles and Heat Flux Values

Figures 24 through 29 present measured temperature values using type T (copper constantan) thermocouples at three locations in each of six wall sections in the building. The three temperatures monitored are the inside surface of the stucco just in from the exterior (except on the north wall, where no stucco is present; in the north wall, this outer thermocouple was placed in the mortar joint of the bricks), the inside surface of the brick layers, and the inside of the insulation on the warm side of the batt insulation.

The peak temperature reached on the inside of the stucco (Figure 24) was approximately 50°C for Location NW1 (North West corner of the building facing west at floor level 1). The corresponding outdoor air temperature peak was approximately 30°C indicating the effect of the sun in raising the sol-air temperature of the exterior surface of the building. The temperature difference between the red line (inside stucco) and the green line (inside brick) is relatively small in colder weather compared with the temperature difference between the inside of the insulation (blue line) and the inside of the brick (green line.) The wall insulation (approximately RSI 3.5 to

4.5) is responsible for the large temperature difference between the inside of the insulation and the inside of the brick. As can be seen from the figure, there are periods in the fall of 1997 (day 285 to day 365–October 15 to December 31), the spring of 1998 (day 405 to 455–February 24 to March 31), and the fall of 1998 (day 650 to day 680–October 12 to November 11) in which freeze thaw cycles (fluctuations around 0°C) were measured in the exterior stucco on this wall.

In Figures 25, 26, 27, 28 and 29, similar graphs are presented for the other five wall locations where heat flux transducers are located. In Figure 27 the green line or inside brick temperature showed some anomalies around approximately Day 380. This was due to a loose thermocouple wire which was subsequently repaired. The north facing wall (Figure 29) experienced the lowest peak temperature (36°C) at the outermost thermocouple, as the direct solar radiation striking the north wall is limited compared with the other walls.

Figures 30 through 40 present the heat flow meter voltage generated by the thermopiles located on each heat flux transducer. Positive values indicate heat flow from the building to the outdoors. As can be seen from Figures 30 through 40, the overwhelmingly dominant heat flow direction is positive, with only a small fraction of the readings during the summer period indicating conduction heat transfer from the outside to the inside. The heat flows in the negative direction are also small compared to the heat flows in the positive direction. If the building had air conditioning, the magnitude of the heat flows from outside to the inside would have increased. The properties of each of the 11 heat flux meters are presented in Table 3. Each of the heat flux meters was made of a calibrated piece of expanded polystyrene beadboard approximately 26 mm thick and 300 mm on each side; however, different thermal conductivities were used for different heat flux meters, and therefore the heat flux meter constant as measured in watts per square meter per millivolt varies for each of the heat flux meters.

Table 3. Heat Flux Transducer Properties

Heat Flux Meter No.			**R value for thickness used in lab test** $\left(\frac{m^2\,°C}{W}\right)$	**Thickness During Lab Test (mm)**	**Thickness on Site (mm)**	**Constant for the Heat Flux Meter (W/m^2 /mV)**
NW1		439-81-1	2.036	76.00	25.9	4.45
W2	Upper	439-84-2	1.547	75.95	25.5	5.96
	Lower	439-84-1	1.547	75.95	25.8	5.89
E3	Upper	439-77	1.960	75.76	25.8	4.64

	Lower	439-83	1.570	75.7	24.6	6.06
SE4	Upper	439-86-2	1.990	76.29	25.9	4.58
	Lower	439-86-1	1.990	76.29	25.8	4.60
NW4	Upper	439-80	2.031	75.91	25.9	4.46
	Lower	439-78	2.048	75.86	26.0	4.41
N4	Upper	439-81-2	2.036	76.0	25.9	4.46
	Lower	439-87	2.000	76.4	25.8	4.58

In Figure 38, some anomalous data is present. High millivolt output readings (values greater than 10 millivolts) are present for two periods. It is possible that electrical interference from some electronic equipment such as a television set may have caused this interference. As can be seen from the graph, the voltage outputs of the heat flux meters are in millivolts, and are susceptible to electrical interference. The remainders of the readings appear to be satisfactory.

2.4 Wall Insulation Thermal Resistance Values

Figures 41 through 51 present the calculated R-value for the glass fiber batt insulation in the 11 different wall sections throughout the building. The R-value was calculated using the temperature difference measured across the insulation, the millivolt output from the heat flux transducer, and the constant for the heat flux transducer as shown in Table 3. The R-value is calculated using the following equation:

$$\text{R-value} = \frac{\text{temperature difference in degrees Celsius } (^{\circ}\text{C})}{\text{heat flux output (mV)} * \text{calibration constant for transducer } (\text{W/m}^2\text{-mV})}$$

Because of time delays related to thermal storage in the heat transfer through the walls, the R-value calculated is not a constant in time; however, during colder periods when the heat flux is consistently in one direction the R-values tend to remain relatively constant over time. Different insulation placement approaches were used in the various walls through the building. There were two different placements: in a number of wall sections an RSI 3.5 nominal batt was placed between the 38 by 89 mm wall studs. In the other wall sections an RSI 2.1 batt was placed horizontally behind the studs and then a RSI 2.1 batt placed vertically between the wood studs. In this case the nominal RSI value is approximately 4.2.

Because there were a limited number of channels on the data logger, only one thermocouple was used to measure the temperature on the room side of the insulation at each of the six wall locations where the heat flux meters were located. In walls W2, E3, SE4, NW4, and N4, there were two heat flux meters installed, one in the lower part of the wall, and the other in the upper part of the wall. The exact placement of the thermocouples and the heat flux meters is shown in figures 3 to 8 of Interim Report #1 (Appendix 1). In the figures the thermocouple measuring the room side insulation temperature is marked as HFT TC. As the suites were occupied, it was difficult to ensure that the occupants did not place furniture and/or boxes against the wall. A further problem that occurred was that in two locations (NW1 and N4) gypsum board and wood stud closets were built on the inside of the wall, and the tenants used the closets for storage.

In Table 4 there is a comparison of the RSI values as installed with the measured RSI values using the heat flux and temperature difference data.

Table 4. Comparison of Installed R value and Measured R Value of Wall Sections

Location		**Installed R value** $\left(\frac{m^2\,°C}{W}\right)$	**Measured R value** $\left(\frac{m^2\,°C}{W}\right)$
NW1		4.2	5.4**
W2	Upper	4.2	3.2
	Lower	4.2	3.3
E3	Upper	4.2	3.8
	Lower	4.2	3.4
SE4	Upper	3.5	4.5
	Lower	3.5	4.2
NW4	Upper	3.5	4.3
	Lower	3.5	4.2
N4	Upper	3.5	4.3**
	Lower	3.5	3.2**

** Measured values at these locations are not considered accurate as the temperature sensors measuring the temperature drop were not in the same part of the wall as the heat flux meters, and gypsum board and wood stud closets were built on the inside of the wall.

Because of the problems encountered with the use of this technique, the measured results presented in Table 4 should be regarded as only approximate. An illustration of one of the problems with the placement of the thermocouples may be seen from Figures 44 and 45. At about Day 333 (November 30, 1997) , the measured RSI values drop at both locations in Wall E3 by approximately RSI 0.5 until about Day 365 (December 31, 1997). It is likely that someone placed a box or other material against the wall where the thermocouple measuring the temperature on the warm side of the insulation is located. The box would reduce the temperature at the thermocouple, and as a consequence the "measured" RSI value drops. In Interim Report Number 3, there are some photographs (Figure 1) showing boxes stacked against the wall at the E3 location. In Figure 49, a similar problem likely occurred, in that a thermocouple at the NW4 location was affected by the presence of a material with some insulating properties placed against the wall during part of the time of the measurements.

The measured values for the insulation agreed with the installed values within -24% and +28%. The reason that the measured values were generally low in the case where two batts (RSI 2.1 and RSI 2.1) were in series is not known. It is also not known why the measured R values were generally high in the case where a single batt (RSI 3.5) was used.

In future installations of this type, particularly in occupied dwellings, the thermocouples should be located exactly in line with the heat flux meters in locations unlikely to be obstructed by furniture, shelving, appliances, etc.

2.5 Pressure Differences Across the Walls

Figures 52 through 57 present plots of the pressure differences at six wall locations as measured by transducers. The red line indicates the pressure difference across the brick wall and the green line indicates the pressure difference across the stud wall. The sums of the two pressure differences represent the total pressure difference across the wall. As a frame of reference, a positive pressure difference shown on the graph indicates that the pressure outside of the building is positive relative to the inside. As can be seen from Figure 52 for the NW1 location, the pressure difference across the brick wall is substantially greater than the pressure difference across the stud wall. This indicates that the brick wall with the outer stucco layer and the inner parging layer has a better air tightness than the stud wall. (Note that there was no stucco layer on the front (north) side of the building. Although the original parging layer on the inner surface of the brick walls was not completely intact after the walls were retrofit, the parging did provide some air tightness, as the brick wall on the north side of the building had approximately the same relative air tightness compared with the wood stud wall as did the walls on the other three sides of the building.)

One of the difficulties in sealing the polyethylene vapour barrier on the inside of the walls was maintaining continuity of the barrier at the floor levels. The brick wall, which has an interior parging layer, along with the exterior stucco, provided a greater air tightness layer than the wood stud wall with the polyethylene barrier.

The ventilation system in the building, a 100% outside air system, was found to be providing consistently greater exhaust air in the building than supply air. Thus, even in the upper floors in winter time the pressure difference across the wall was generally positive (i.e. the pressure outside the building was greater than inside).

As can be seen from Figures 52 through 57, the half-hourly average pressure differentials across the walls were relatively modest. The highest value measured was 31 Pascals averaged over a half hour interval for the NW4 location. These peak pressures occurred a number of times throughout the monitoring period. By comparing Figure 52 (NW1 location) with Figure 57 (NW4 location), it can be seen that more peak pressures were experienced at the top part of the wall. At the higher elevation, fewer obstructions from other buildings are present, and the wind velocity is generally higher.

2.6 Wall Cavity Humidity

Plots of the wall cavity relative humidity are presented in Figures 58 through 63. The relative humidity sensors are located between the glass fibre insulation and the brick wall. The six sensors are located in the same six wall section locations where the wall heat flux measurements are located.

As shown in Figure 61, the SE 4 wall cavity had initially quite high relative humidity (approaching 80%); most of the other wall sections had a considerably lower initial relative humidity. The SE4 wall cavity was where the water penetration experiment had taken place in August 1996. The average relative humidity in this wall section was approximately 60% toward the end of the monitoring period. Most of the other wall sections had values that were slightly less except for the NW4 wall cavity which had humidity values in the 80% range. The NW4 location is on a corner of the building, and it is likely that the corner receives more wind-driven rainfall.

As shown in Figure 60, the E3 wall cavity RH sensor exhibited an instrument failure and the values beyond Day 560 (July 14, 1998) are invalid due to deterioration of the sensor. As the sensor is permanently fixed inside the wall, it was not possible to repair the sensor.

The absolute humidity values for the wall cavities are plotted in Figures 64 to 69. The absolute humidity was calculated based on the relative humidity and the temperature at the sensor. The absolute humidity drops considerably in the colder weather and rises during the warmer weather. In general, the absolute humidity curves inside the wall cavity tended to mimic the absolute humidity measurements outdoors. This can be seen by comparing, for example, Figure 64 with Figure 6. Because of the presence of the brick inside the wall, the short-term fluctuation in the absolute humidity in the wall cavity is reduced. The brick acts as a damper in terms of reducing the short-term oscillations in absolute humidity compared with that experienced outdoors.

2.7 Brick Wall Onysko Moisture Sensors

Figures 70 through 75 present the results of the moisture content as measured by the Onysko sensors located 89 mm outward from the interior of the brick in a mortar joint on the exterior wall. The Onysko sensor is a piece of wood material of precise thickness with electrodes on two sides. The data logger measures a DC resistance of the wood material, and the resistance reading is converted to a moisture content. For Wall NW1 (Figure 70), the moisture content values are quite low, being less than 13 % during the monitoring period. However, it is interesting to note that around Day 540 (June 24, 1998), the moisture content starts to rise considerably. As can be seen from the rainfall data in Figure 16, there was a large rainfall on Day 540. In various half hour periods there were rainfall values of approximately 4, 7 and 17 mm in half hour periods that day, and the moisture content rises in NW 1 (Figure 70). The same effects can be seen with the sensors located at W2 (Figure 71), at E3 (Figure 72) and (N4) (Figure 75) The N4 location is brick with no stucco on the exterior; thus, the possibility of rain penetration is relatively high. Whereas the previously mentioned three sensors (NW1, W2, E3) generally had peak moisture content values less than 16%, the sensor in N4 rose to approximately 23.5% during that period after the wet interval.

For the SE4 location, generally the moisture contents were higher, with values ranging to 30%. The phenomenon here dates back to the time when the water penetration test was performed on this wall in August of 1996. At Day 540, there is no indication of a rise of moisture content in the wall, indicating no further penetration of water at this site. For sensor NW4 (Figure 74), there is some inaccuracy in the readings. It is very unlikely that the moisture content would drop as low as 0%. One of the problems with wood moisture content readings is that when moisture levels get below about 7%, the electrical resistance of the Onysko sensor goes very, very high and with very high resistance there are very small currents involved and the accuracy of the measurement falls off. The sensor at NW4, however, indicates that very little moisture is present in the wall. The following table summarizes the data gathered from the Onysko Moisture Sensors.

Table 5. Onysko Moisture Sensor Outputs Over the Monitoring Period

Location	Onysko Sensor Output (over the monitoring period)
NW1	Dry In the range of 7.8-12.5% moisture content over the monitoring period. Increased to 12.5% after day 540 (June 24, 1998) and then returned to 8-10%
W2	Dry In the range of 7.8 -13% moisture content over the monitoring period. Increased to 12.5% after day 540 and then returned to 8-10%
E3	Dry In the range of 7-16.2% moisture content over the monitoring period. Increased to 16% after day 540 and then returned to 8-11%
SE4	Wet, slowly drying In the range of 18.5 to 32.5% moisture content over the monitoring period.
NW4	Slightly moist In the range of 6.5% to 19.2% moisture content over the monitoring period
N4	Wet period following day 530 (June 14, 1998) In the range of approximately 4% to 23.5% moisture content over the monitoring period.

2.8 Brick Wall SRC Moisture Sensors

Figures 76 through 81 present the monitoring results from a special moisture sensor consisting of a filter paper separated by two electrodes. The filter paper is an electrical resistance in parallel with a 178 kohm resistor. The reason that a 178 kohm resistor was placed in parallel with the filter paper electrodes was that the maximum resistance that the data logger could measure was 200 kohms. Rising resistance is shown on the graph as an indication of a drier condition; falling resistance indicates a wetter condition. A dry condition would indicate 178 kohms. These moisture sensors were located adjacent to the Onysko sensors. The results of the continuous measurements on the sensors are presented in Table 6.

Table 6. SRC Moisture Sensor Outputs Over the Monitoring Period

Location	SRC Sensor Output (over the monitoring period)
NW1	No change--dry condition
W2	No change--dry condition
E3	No change--dry condition
SE4	Low resistance (wet) initially, followed by gradual trend to dry condition; considerable variation over time
NW4	Small decreases in electrical resistance, returning to dry condition
N4	Dry condition initially, with fall in resistance starting about day 530 (June 14, 1998), followed by return to dry condition

The SRC moisture sensors indicate, as do the Onysko sensors, the presence of moisture in contact with the sensors. The SRC sensor was initially developed to indicate the presence of water passing through the brick wall in the water penetration test done on the South East 4 wall in August of 1996. The SRC sensor has little mass to it; thus it can rapidly detect the presence or absence of a liquid. This advantage, however, is a relatively minor one. The Onysko sensor, which exhibits characteristics similar to moisture pins driven into wood materials, can also measure the presence of a liquid. In addition, the Onysko sensor can also give an indication of the wood moisture content. The SRC sensor is unable to do this.

In comparing Table 5 with Table 6, the SRC sensor was able to provide the same assessment of a dry condition as the Onysko sensor for walls NW1, W2, and E3. The Onysko sensor, however, is more suitable for providing a quantitative, as opposed to a qualitative measure of the amount of moisture present in the wall systems, as was the case for walls SE4, NW4, and N4. Thus the Onysko sensor is the superior sensor for this type of application.

2.9 Attic Conditions

The attic temperature is presented in Figure 82. A comparison of the attic temperature with the outdoor temperature is shown in Figure 83; the green line represents the outdoor temperature. As can be seen, in the period around following Day 365, the attic temperature is considerably warmer than the outdoor temperature. A plot of the attic temperature versus the outdoor temperature is shown in Figure 84. At the colder outdoor temperatures, the attic air temperature is considerably higher than the outdoor temperature, even though the attic insulation level is RSI 4.9. There are several possible explanations for this. The explanations include the following:

a. Convective air flow from the upper floor into the attic space because of holes in the ceiling of the upper floor.
b. Convective heat flow through the low density glass fibre insulation in the attic at lower temperatures. The attic insulation level was a nominal RSI 4.8 using blown glass fibre insulation.
c. Solar heat gains from the brick wall above the upper floor into the attic space.
d. Solar heat gains from the roof.
e. Snow buildup on the roof, which adds an additional insulating layer.

This phenomenon of attic temperatures being warmer than outdoor temperatures, even when the attics are ventilated , is well-known for its ability to cause ice dams and moisture damage on shingled roofs. As the apartment building has a continuous roof membrane, the possibility of water damage is much less likely than with a shingled roof.

A plot of the attic relative humidity measured over the monitoring period is presented in Figure 85.

In Figure 86, the absolute humidity for the air in the attic is plotted as a function of time. Figure 86 may be compared with the absolute humidity of the outdoor air which is found in Figure 6. In general, absolute humidity values are low in winter and reach a peak during the summer months.

In Figures 87 to 89, plots are presented of the attic joist moisture content. For the center of the attic, the moisture content is relatively high, reaching a peak of around 21% at day 430 (March 6, 1998). During the summer period the moisture content falls off. The north attic joist moisture content is shown in Figure 88 . Here the moisture contents are lower, reaching a peak of about 17.5%. In the south attic joist (Figure 89), the moisture content is lowest, reaching a peak of 15%. There are greater solar heat gains from the brick wall adjacent to the attic on the south side of the building. With the higher temperature in the south side of the attic, the joist moisture content would be smaller than that found in the center of the attic even though the absolute humidity in the attic would be relatively uniform at any point in time.

The wood moisture contents of attic joists that are resting on the inside of the north brick wall are plotted in Figures 90 to 92. The north brick wall is of particular interest, as this wall was not covered with stucco; in addition, the attic joists are structurally supported on their ends by the brick wall. The joists penetrate the brick wall by approximately one brick width. Generally the moisture content values were low, well under the 19% standard for kiln dried lumber. However, at approximately Day 535 (June 19, 1998), the moisture contents at the ends of the three joists rose fairly dramatically. As can be seen from the rain gauge data (Figures 16,17,19), there was a relatively high amount of rainfall from about day 530 until about day 560. In the West joist, the moisture content reached a peak of 22.5% on day 562 (July 16, 1998); in the center joist the moisture content peaked at 20.5%, and in the East joist the moisture content peaked at 16.8%. These elevated moisture content values indicate that liquid water has passed through the mortar joints in the bricks and into the end of the joists. Fortunately the moisture content falls off relatively quickly after the period in which the moisture content rises above 20%. Thus, there was little likelihood of wood rot occurring; if, however, sustained rainfall and water leakage through the wall over a longer period were experienced, there would be the possibility of some wood rot. For the period around June, July, and August, 1998, however, the joists did dry out after the wetting incident.

In retrospect, it would have been desirable to have placed wood moisture sensors in the ends of other attic joists and beams resting in the east, west and south brick walls. These moisture sensors would have provided useful comparison data relative to the performance of the moisture sensors at the ends of the joists resting in the north brick wall. The Onysko moisture sensors were placed in the east, west and south brick walls, and their peak moisture content values were all less than 19.2%, with the exception of the SE4 location, where the water penetration tests had been performed in August of 1996.

3.0 WALL WETTING PATTERNS

Photographs were taken of the wetting patterns on the outside walls of the building following a rainstorm. The on-site contractor in Prince Albert was given instructions to take photographs whenever a significant rainfall occurred. As can be seen from Figure 16, the rainfall in Prince Albert during the monitoring period only exceeded 5 mm per half hour period on a few occasions. Only two sets of pictures were taken following rainfalls.

A view of the rainfall pattern on the west wall of the building is presented in Figure 93. The picture was taken after the strong rainfall on Day 558 (July 12,1998). The wind was coming from the northwest direction, as can be seen from the rainfall patterns. The greatest soaking of the stucco occurs on the upper floors. There is a relatively dry zone on the upper left, or northwest, upper part of the building. The cornice for the building provides some protection to the upper northwest corner of the building. Water coming off the window sills predominantly leaves the sills on the downwind, or south side. The water coming off the window sills is not uniform, as the water stains on the walls beneath the windows are not similar in size. (One of the three rain gauges on the roof can be seen above the upper left window on this side of the building.) There is a relatively open area to the north and west of the building.

A view of the rainfall pattern on the east side of the building is shown in Figure 94. Unlike the west side, this side of the building is influenced by adjacent buildings. Water has likely spilled over the parapet in a number of locations, as evidenced by the water stains coming from the top of the parapet. A view of the parapet and the sloped metal cover for the parapet are presented in Figure 18. As can be seen, it is relatively easy for wind-driven water on the roof to spill over the parapet in a strong wind. The water spilling off the window sills is predominantly coming off on the north edges of the sills, although some windows have the water spilling off the south edges. A water stain is also present near the north end of the east wall at approximately the same height as the bottom of the window two floors down from the top. (One of the rain gauges on the roof can be seen above the upper left window.)

A view of the rainfall pattern taken from the southwest part of the building is shown in Figure 95. Although the picture is relatively faint, one can see some spillover of water from the parapet near the chimney and also near the southeast upper corner.

4.0 ENERGY PERFORMANCE OF THE APARTMENT BUILDING

The building has individual metering of the electrical consumption in each suite. Each suite has an electric stove and refrigerator, but no dishwasher or in-suite washer and dryer. In each suite there is a 3 kilowatt wall-mounted electric heater. These heaters were installed by the owner as a means of reducing potential complaints about lack of heat during the shoulder seasons (late spring and early fall). Because of the relatively warm temperatures found in the building, however, the electric heaters are seldom used. On each of the four floors there is a coin-operated clothes washer and an electric dryer.

The building is heated using three natural gas fired, atmospheric-vented boilers with pilot lights. The boilers were used units. One boiler heats a glycol mixture which is then used to transfer heat to a heating coil in the incoming outside air supply for the building. The remaining two boilers supply heat for the radiant floor heating used on the upper three floors and the baseboard hydronic heaters on the lower floor. Each of these three boilers had an individual natural gas meter installed for monitoring.

The domestic hot water for the building is supplied from a single natural gas fired, atmospheric - vented water heater with a pilot light. A circulating pump runs 24 hours per day to provide hot water instantaneously at the taps throughout the building. A natural gas meter was placed on the water heater also.

Aside from the natural gas boilers and the water heater, there is no other natural gas equipment.

4.1 Electrical Energy Consumption

In Figure 96, a plot of the total average electrical consumption for each two-week monitoring period versus the heating degree days per day is presented. This consumption is the sum of the electrical consumption of the individual apartments (lighting and appliances) plus the consumption of the corridor lighting, clothes washers and dryers, outside lighting, fans, and pumps.

The total electrical consumption of the building does not vary very much with the heating degree days per day. The Y intercept is 10.9 kilowatts and the slope is 0.024. The average for the readings is 11.2 kilowatts. In Figure 97, the common area, or central building electrical meter consumption is plotted; the y intercept is 4.46 kilowatts and the slope is 0.015. The average is 4.66 kilowatts. This consumption consists of all the electricity consumption for the building excluding the consumption of the individual suites.

The following table summarizes the end uses of the electrical consumption in the building:

Table 7. Electrical Consumption

Electrical End Use	Average power consumption (kilowatts)	Percentages
Common area lighting, clothes washers and dryers, outside lighting, central ventilation supply and exhaust fans, boiler and water heater pumps	4.66	41.6
Individual suite consumption (lights, appliances, radios, televisions, etc) Total for 30 suites = 6.54 kW or 0.218 kW/suite	6.54	58.4
Totals	**11.2**	**100**

Almost all of the refrigerators used in the building are older frost-free units. Newer models with lower energy consumption would help to reduce the individual suite electricity consumption.

4.2 Natural Gas Consumption

The total natural gas consumption of the facility is plotted versus the heating degree-days per day in Figure 98. The Y intercept has a value of 13.5 m^3/day and the slope is equal to 7.84 m^3/heating degree day. The R^2 value for the linear curve fit is 0.940. The R^2 value is a measure of the linearity of the correlation between the y and x axes. If the curve were an exact straight line, the R^2 value would equal 1.0. The Saskatchewan Research Council has performed similar plots analyzing the natural gas consumption of more than 50 commercial buildings. Generally the R^2 values on the plots exceed 0.90.

If the natural gas consumption rate in figure 98 is extrapolated to the outdoor design temperature -37 °C (55 heating degree-days per day), the consumption rate would equal 445 m^3 per day or 656,000 Btu/hour (192 kilowatts). The measured input capacity of the three boilers (one for ventilation and two for space heating) amount to the following. The measured capacity of the boilers was determined using the natural gas meter on the boiler plus a stopwatch:

Table 8. Measured input capacity of the three boilers

Boiler End Use	Measured Natural Gas Consumption Rate Btu/hour
Ventilation	390,000
Space Heating No. 1	428,000
Space Heating No. 2	418,000
Total	1,236,000 (362 kilowatts)

As can be seen from the above table, the measured input capacity for the three boilers is 362 kilowatts, and the measured natural gas consumption of the entire building extrapolated to outdoor design conditions is 192 kilowatts (including natural gas consumption for water heating). Thus the building has ample reserve capacity for space heating. One of the two space heating boilers could be turned off completely and could be used as a spare.

A plot of the natural gas consumed by the boiler which heats the ventilation air is shown in Figure 99. There is a considerable scatter with the points because the thermostat setting was varied during parts of the year. The Y intercept is 4.896 and the slope is 2.06 m^3/heating degree day. The R^2 is relatively poor at 0.788. Using this data, and extrapolating to a year with long term average heating degree days of 6437 °C-days, the annual consumption for the ventilation air would amount to 15,047 m^3.

If the ventilation boiler's natural gas consumption in Figure 99 is extrapolated to -37 °C, the consumption would equal 174,000 Btu/hour (51 kW). As can be seen from the above table, the capacity of the ventilation boiler (390,000 Btu/hr or 114 kW) greatly exceeds the measured consumption extrapolated to design conditions (174,000 Btu/hr). Thus the ventilation boiler has ample capacity for the current outside air flow.

In Figure 100, the natural gas consumption for space heating, that is, the natural gas used for the non-ventilation space heating is shown. The Y intercept is equal to -8.80 and the slope is 5.67.

The R^2 value is 0.93. Extrapolating to a year with long term heating degree days of 6437 °C-days, the annual consumption for space heating would amount to 33,285 m^3.

The natural gas consumption for domestic water heating averaged 24.2 m^3/day.

A summary of the total energy consumption of the building for a one-year period is presented in Table 9.

Table 9. Measured Energy Consumption of the Building Over One-year Period
(The heating consumption is normalized to an average year
with 6437 Celsius heating degree-days.)
Total floor area based on outside dimensions equals 1681 m^2.
The usable floor area based on the inside dimensions of the outer walls equals 1522 m^2.

	Energy Consumption	Gigajoules	%
Total Electricity Consumption	98,112 kWh	353	100
Electricity Consumption by common area uses and heating and ventilating systems	41,894 kWh	151	42.7
Electricity Consumption by individual suites	56,218 kWh	202	57.3
Total Natural Gas Consumption	55,394 m^3	2,066	100
Domestic Water Heating	8,848 m^3	330	16.0
Ventilation Boiler	13,260 m^3	495	24.0
Space Heating Boilers	33,286 m^3	1,241	60.0

4.3 Computer Model of the Building

The HOT 2000 program was used to model the energy flows in the building. A special version of the HOT 2000 program (Version 7.15f) was secured from Brian Bradley of UNIES Ltd. This special version allows one to use a larger interior volume, larger ventilation flows, and larger internal gains than the standard HOT 2000 program.

All of the physical dimensions were input for the building; in addition, the internal heat gains from actual electrical use, from people (estimated at 28 occupants), and from the use of domestic hot water were used as inputs to the program. The measured supply and exhaust flows for ventilation were also used.

In Interim Report Number 4, some outputs from the computer model of the building were presented. Subsequent to that report, it was learned from Brian Bradley that an error existed in the computer model algorithms related to the air infiltration component. A revised version of the program (Version 7.15h) was secured from Mr. Bradley and the computer simulations were repeated.

The following table shows the percentage breakdown of the heat losses in the building as calculated by the computer program:

Table 10. HOT2000 Calculation of Annual Space Heating Loads-- Building As Is (1998)
Total Natural Gas Consumption including DHW = 2510 Gigajoules (GJ)
DHW Natural Gas Consumption = 333 GJ
Total Space Heating and Ventilation NG Consumption = 2177 GJ
Boiler Losses Due to Inefficiency (Seasonal Efficiency of 65.6%) = 647 GJ
Net Space Heating and Ventilation NG Consumption (excluding boiler losses) = 1428 GJ

Building Element	**Percentage of Space Heating Annual Consumption excluding boiler losses (%) [As calculated by the HOT-2000 Program]**
Ventilation and Air Change	66.9
Ceiling	2.6
Walls above grade excluding windows and doors	16.4
Walls below grade	1.3
Basement floor perimeter	1.5
Basement floor center	1.9

Windows	8.4
Doors	0.9
Totals	**99.9**

The ventilation and air change heating consumption is a very high percentage (66.9%) of the total space heating consumption excluding boiler losses. Other major components such as the walls above grade (16.4%), windows (8.4%), and ceiling (2.6%) are small in comparison.

The HOT-2000 calculation of the total air change including ventilation amounts to 0.94 air changes/hour or 1447 L/s. The measured air supply flow for the building is 450 L/s, and the measured exhaust flow is 1159 L/s. The difference between the measured exhaust flow (1159 L/s) and the HOT-2000 calculation of total air change (1447 L/s) equals 288 L/s and is the computer program's calculation of infiltration for the building.

As noted in the computer program, the excess of the exhaust flow for the building (1159 L/s) over the supply flow (450 L/s) is sufficient (709 L/s) to cause a negative pressure in the building equal to more than 5 pascals. As the building is not very tall–3.5 stories above grade– the stack effect due to the inside-outside temperature difference is unlikely to overcome the negative pressure in the building caused by the mechanical system except in very cold weather. As can be seen from Figures 55, 56, and 57, the sum of the two pressure differences across the walls at the third floor pressure taps at the SE4, NW4, and N4 locations is almost always positive (indicating a positive flow from outdoors to indoors), indicating that exfiltration is almost always negligible. As a consequence, the actual air change in the building should be close to or equal to the exhaust flow divided by the building volume, or 0.753 air changes per hour. However, the algorithms in the computer program calculate an average air change rate of 0.940 ac/h. If the air change rate is decreased from 0.94 ac/h to 0.753 ac/h, the heat loss from the building associated with air change falls by 239,000 Megajoules.

It is likely that the lower air change rate of 0.753 ac/h more accurately models the performance of the building. In section 4.5, further discussion on this point is included when a comparison is made of the measured natural gas consumption of the building with the computer model prediction.

4.4 Heat Gains as Calculated by the Computer Model

The heat gains for the building are as follows:

Table 11. Building Heat Supplies for Space Heating: (Karcher As Is--1998)
HOT-2000 Calculation

Usable Internal Gains	15.8%
Usable Solar Gains	4.9%
Heat Supplied by Boilers	79.3%
Total	**100%**

The solar gains are relatively low because of the small window areas on the south side, large windows on the north, and modest window areas on the east and west of the building.

4.5 Energy Consumption Analysis Under Different Scenarios

The computer model was run using several different scenarios.

The results are presented in Table 12.

Table 12. HOT-2000 Calculations Using Varying Assumptions

Building Assumption	Annual Space Heating and Ventilation Natural Gas Consumption (GJ)	Average Annual Air Change Rate (ac/h)
As is (1998)	2180	0.94
As is but with balanced ventilation at 775 L/s (0.5 ac/h)	1920	0.77
As is, but with 65% effective heat recovery on 775 L/s of balanced air flows	1420	0.77

As can be seen from the above table, the ventilation and air change rate have a great effect on the heat loss of the building. Had the building ventilation rate been reduced to 0.5 ac/h, and heat recovery installed on the ventilation air, the annual space heating and ventilation load of the building would be reduced from 2180 GJ to 1420 GJ, a reduction of 35%.

4.6 Comparison of Computer Model Output With Measured Gas Consumption

A comparison of the measured natural gas consumption of the building (ventilation boiler, two space heating boilers, and domestic water heater) with the output of the HOT-2000 analysis of the building was done. Inputs to the computer model included all the physical dimensions of the building along with the known internal heat gains from electrical use in the building and the efficiency of the boilers, and the known supply air and exhaust air flows.

The results for a standard year with long term average heating degree days are as follows:

Table 13. Measured and Computer Prediction of Annual Natural Gas Consumption

	Annual Space Heating and Ventilation Natural Gas Consumption (GJ)	**Total Annual Natural Gas Consumption including DHW (GJ)**
Measured Value (post-retrofit)	1736	2,066
Computer Prediction (post-retrofit)	2180	2,510

The computer prediction of energy consumption for space heating and ventilation (2180 GJ) is substantially higher (25.5%) than the measured value (1736 GJ) for the building. An interesting feature of the building's operation is the strong negative pressure experienced due to the excess of mechanically exhausted air (1159 L/s) compared with the supply air flow (450 L/s). As the entire building is under a negative pressure compared with the outdoor air, there is likely to be a "dynamic insulation" effect in which some of the conducted space heat to the outside is recovered by the air entering the walls and ceiling. This effect is not modeled in the HOT-2000 program.

As was mentioned in Section 4.2 of this report, the computer prediction of the annual heat loss associated with the air change in the building is very likely over-estimated by approximately 239 GJ of heat loss or, 364 GJ of natural gas consumption . If this amount of heat loss is subtracted from the computer prediction, the agreement between the measured consumption and the modified computer prediction is improved. The ratio of the computer prediction to the measured value equals 1.046, indicating a much closer agreement between measured and predicted consumption.

5.0 DISCUSSION

5.1 Moisture Performance of the Masonry Wall

The addition of stucco to the masonry walls has reduced the likelihood of water movement into the masonry wall, based on the moisture readings from the wall locations. As shown by the moisture sensors, the locations with the stucco on the exterior experienced much smaller rises in moisture content than did location N4 where no stucco is present. The ends of the attic joists that bear on the north brick wall all experienced a rise in moisture content following the heavy rain in June 1998, as liquid moisture can readily pass through the brick. Fortunately, enough drying occurred following this rain that wood rot would not occur.

The brick wall with no stucco is more vulnerable to rain penetration than the brick walls with no stucco.

5.2 Freeze-thaw Risk of the Clay Brick

It is only the north side of the building that has clay brick exposed to the weather. Saskatchewan has a long history of use of clay brick as an exterior cladding on dwellings, including dwellings with insulated walls. The performance with regard to avoiding freeze-thaw damage has generally been excellent, due to the low rainfall, relatively strong solar drying, and the sustained freezing temperatures in winter. Clay brick is most vulnerable to freeze-thaw deterioration under conditions of high rainfall followed by frequent freeze-thaw cycles.

5.3 Air Barrier Performance of the Masonry Wall

Based on a comparison of pressure drops through the brick wall and the stud wall, the bulk of the air tightness layer is provided by the brick wall. There is a layer of stucco on the outside of the brick walls (except for the north wall), and a layer of parging on the inside of the wall. The following table summarizes the measurements of the pressure drops across the wall, and clearly indicates that the dominant air barrier in the wall is provided by the brick wall.

Although a serious effort was made to install a tight polyethylene air-vapour barrier on the inside of the wood stud walls, the results were only partly successful. The overall air tightness of the building as measured by a CGSB whole building air tightness test was 2.04 cm^2/m^2. For comparison purposes, the standard for R-2000 houses is 0.7 cm^2/m^2. Another measure of air tightness is the air leakage per unit surface area of the building at a pressure difference of 75 pascals. The value for the apartment building was 2.22 $L/s\text{-}m^2$ at a pressure difference of 75 pascals. It was very difficult to achieve continuity of the air-vapour barrier at the floor level, as shiplap boards with substantial gaps between the boards extended out past the plane of the polyethylene air-vapour barrier.

Table 14. Brick wall pressure difference as a percentage of the total wall pressure difference

Wall	Brick Wall Pressure Difference as a Percentage of the Total Wall Pressure Difference (%)
NW1	77
W2	88
E3	76
SE4	75
NW4	92
N4	76

In similar projects of this type in future, it will be important to develop details and techniques that can address the air leakage that can occur at the floor levels.

5.4 Weather Conditions and Wetting Patterns

Prince Albert has annual average heating degree-days of 6437 °C-days (base 18 °C). During the 12-month period from September 1997 to August 1998 (this period includes all the heating season months during the 97-98 winter), the accumulated degree-days were much less, at 5377 °C-days. The winter of 97-98 was unusually mild, influenced by the El Niño phenomenon.

The rainfall experienced in June 1998 amounted to 120.5 mm, or roughly double the long term average of 66.9 mm. Rainfall during that month included one period with 17 mm of rain in a half hour period, as measured by two of the rain gauges on the building. This intensive rain resulted in some movement of liquid through the brick wall on the north side of the building. The moisture pins indicated, however, that drying of the attic joists in the north wall took place after this rainfall event. The walls that were covered with stucco did not experience any significant wetting at the moisture pin locations.

Accompanying strong winds also blew some of the water on the roof over the top of the parapet onto the walls of the building on the east and south sides. Photographs of the wetting patterns associated with that intensive rainstorm indicated non-uniform wetting of the walls.

5.5 Energy Use Before and After the Retrofit

The measured natural gas consumption values for the building before and after retrofits are presented in the following table:

Table 15. Comparison of natural gas consumption before and after retrofit

Year	**Annual Natural Gas Consumption (Gigajoules)**	**Annual Natural Gas Consumption (Gigajoules)** **normalized to average annual heating degree days of 6437 °C-d**
Pre-retrofit October 11, 1994 to October 16, 1995 (370 days)	1,688 (Value adjusted to 365 days)	1,718
Post-retrofit	2,066 (Value adjusted to 365 days)	2,066

In the Post-retrofit condition, the breakdown of natural gas energy use was as follows for an annual year normalized to the long-term average heating degree days.

Table 16. Post-Retrofit Annual Energy Use

	Annual Natural Gas Consumption (Gigajoules)
Total Natural Gas Consumption	**2,066**
Domestic Hot Water	330
Space Heating Boilers	1,241
Ventilation System Boiler	495

As can be seen from the above table, the natural gas consumption of the building increased in the post-retrofit case. Although the insulation was upgraded in the building, the addition of the mechanical ventilation system resulted in a substantial increase in the energy consumption related to air change. The indoor air quality was greatly improved by the ventilation system, however, resulting in a more attractive indoor environment. With the lowered relative humidity, the incidence of mold and mildew smells was completely eliminated. The newer heating system with individual suite thermostats for the heating system allowed the tenants to better control the suite temperatures.

5.6 Indoor Environment After the Retrofit

A more complete report on the indoor environment measurements is presented in Interim Report Number 4, dated June 1998 (Appendix 1). A total of three suites (suite numbers 113, 201, and 203) had their indoor environment tested for a number of parameters using a variety of sensors--formaldehyde, particulates, volatile organic compounds, ventilation rate, carbon dioxide, and relative humidity over the two-week period from February 11 to February 25, 1998.

A summary of the readings is presented in the following table:

Table 17. Summary of Indoor Air Quality Readings

Parameter	Results of Testing	Summary
Formaldehyde	All values below 0.01 ppm; Canadian residential guideline is a target level of 0.05 ppm and an action level of 0.10 ppm	Passes guideline
Particulates	All readings were below 23 µg/m^3; the Canadian residential guideline is 40 µg/m^3	Passes guideline
Volatile Organic Compounds	All readings below 0.38 mg/m^3; the ASHRAE draft guideline is 1.0 mg/m^3	Passes guideline
Carbon dioxide	All mean values less than 569 ppm; peak values of 836, 630, and 1114 ppm for the three suites: Canadian residential guideline is 3500 ppm (Acceptable long term exposure range)	Passes guideline

Relative humidity	Mean values of 5.6%, 5.2% and 9.8 % for the three suites; Canadian guideline is 30% unless constrained by window condensation	Considerably lower than Canadian guideline of 30%
Air change rate	0.97 ac/h, 0.98 ac/h and 0.56 ac/h	No explicit guideline; air change rates in the range of 0.2 to 0.5 ac/h are found in many Canadian houses.

With the exception of relative humidity, all of the three suites tested were able to meet the guidelines for the above indoor air quality parameters.

The building does not have a central humidification system, and is ventilated continuously at an average rate of 39 L/s per suite. The ventilation system is set up so that there is an exhaust port in each room of each suite, ensuring mechanical ventilation is provided to all rooms in the suites. To our knowledge, this is the first time that such a system has been used. More typically, in most apartment buildings, the ventilation air enters the suite and is exhausted through only the bathroom vent and the kitchen vent, leaving other rooms such as bedrooms poorly ventilated or not ventilated at all under some weather conditions. One of the essentials of a good ventilation system is good ventilation effectiveness, i.e., good distribution of the ventilation air through the entire living space, and this building has good ventilation effectiveness.

With the relatively high rate of ventilation and the absence of humidification, the air becomes quite dry in the winter months. The tenants do not use humidifiers, according to the custodian.

The CSA F326 Residential Ventilation Standard recommends a continuous exhaust flow of 30 L/s for a kitchen and 10 L/s for a bathroom, or a total of 40 L/s. The ASHRAE 62-89 Ventilation Standard, however, recommends 12 L/s continuous ventilation (or openable windows) for a kitchen and 10 L/s (or openable windows) for a total of 22 L/s. The apartment building, with an average exhaust flow of 39 L/s per suite, is ventilated at a rate comparable to the CSA recommendation, but at a rate considerably higher than the ASHRAE Standard. As the suites are relatively small in floor area, the air change rate average is high.

5.7 Logistic Problems and Solutions During the Retrofit

A number of construction items used in the rehabilitation were re-used from other projects, including the following:

a. Three heating boilers, two for space heating and one for ventilation air heating.
b. Domestic water heater.

c. Circulation pumps.
d. Heating coil for ventilation air.
e. Glass fiber batt insulation for walls.
f. ABS plumbing piping.
g. Electric stoves.
h. Electric refrigerators.
i. Kitchen cabinets.
j. Interior doors.

In addition to these materials, the basic structure of the building was also re-used, saving greatly the embodied energy in the structure.

This re-use of building materials is generally environmentally sound, and is to be encouraged. Re-used building materials lower the amount of embodied energy in the building. In addition, older materials generally have lower offgassing rates of volatile organic compounds and formaldehyde than newer materials.

One problem that arose in the re-use of older materials concerned the re-used heating coil for ventilation air. The recycled heating coil had a much higher air flow pressure drop than the coil that was specified by the mechanical engineer who designed the supply air system. As a consequence, the supply air flow was lower than the design value. The design value was 992 L/s and yet the measured flow was 450 L/s, or 55% less than design. This lack of supply flow, coupled with the exhaust flow that was 1159 L/s (17% more than design) instead of 992 L/s, resulted in a strong negative pressure in the building, including the mechanical room. The strong negative pressure caused the boilers to backdraft, and as a consequence the smell of combustion products was present in the mechanical room. The problem was compounded by the leakage of air from the mechanical room through the filter housing into the upstream side of the fan that provided the supply air. In an attempt to remedy the problem, the filter housing was moved to the outside of the building and the duct passing through the furnace room was sealed.

This problem points to the need for careful consideration when mechanical system parts are re-used in a building.

6.0 RECOMMENDATIONS

The rehabilitation of the building has improved the indoor air quality, the building aesthetics and longevity, and provided an improved living situation for low income people. The following recommendations relate to improving the ventilation, air sealing, and boiler performance.

6.1 Use of Wood Frame Walls to Insulate on the Inside of Brick Structural Walls.

Based on the results of 15 months of monitoring data, the performance of the three exterior walls of the building (East, South and West) where stucco was used as an exterior coating has been very satisfactory. The exterior appearance has been improved, the rain penetration problem solved, and the longevity of the building has been increased.

On the North wall of the building, however, which was not stuccoed, there was some rain penetration into the ends of attic joists resting on the inner layer of brick in the wall. During the monitoring period the moisture content following a serious rain period rose, but then fell below 19% moisture content, and no damage is anticipated. A second factor of safety in the wall is that the attic joists are resting on an inner wood stud wall which is used to support the batt insulation, and this wall also provides some support to the attic joists.

It is not certain, however, that the ends of the attic joists will be able to withstand repeated rainfalls followed by short drying intervals. A weather pattern with repeated rainfalls and few drying intervals could cause the ends of the joists to rot. Further monitoring of the building over an extended period would help determine the vulnerability of these joists to moisture damage.

6.2 Ventilation Tuneup

At present the supply air flow is 450 L/s and the exhaust flow is 1159 L/s for the building. This excess of exhaust flow causes a negative pressure in the building, and adds to the cost of heating the building. The high exhaust flow relative to the supply flow also contributes to potential problems with backdrafting of the combustion equipment.

As was found by the indoor environment testing, the air quality in the suites tested was good. The ASHRAE Standard 62-89 recommends an exhaust air flow of 22 L/s for a suite with a single bath and kitchen. By reducing the air flow from the current exhaust flow average of 39 L/s per suite, acceptable air quality in the suites could be maintained, and the problem of very low relative humidity values in winter would also be partially resolved.

The following are the recommended actions to address the problems with the supply and exhaust flows in the building.

1. A consulting engineer with HVAC design experience should be engaged to review this report, and the balancing report on the air system.
2. The engineer should become familiar with the current supply and exhaust systems in place .
3. The supply and exhaust systems should be revised so as to provide a balanced flow of air based on ASHRAE Standard 62-89. Particular attention should be paid to air leakage problems with the existing exhaust system ductwork.

Correction of the problems with the air system will result in a better distribution of air exhaust in each of the suites, and also will reduce the space heating costs in the building. A reduction of approximately 25% in the space heating cost of the building is possible if this change is made.

6.3 Air Sealing of the Building

A company with experience in infrared thermography should be hired to perform an investigation of air leakage in the building. During the whole building pressure test, it was noticed that a considerable amount of air infiltration occurs in the front part of the building underneath the entrance stairs. Other potential spots for air leakage include the attic hatch, and the storage room adjacent to the mechanical room. By reducing unnecessary infiltration, the heating bills in the building can be reduced.

6.4 Boiler Controls

At present the boilers operate at a fixed liquid temperature. By adding an outdoor air reset control to the boilers, the liquid temperature could be reduced in the warmer weather and energy saved. Savings of the order of 15% have been measured in some controlled experiments using outdoor air reset controls.

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INTERIM REPORT #1

The Renovation of an Apartment Building with Solid Masonry Walls

for

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SRC Publication No.
I-4800-9-C-97
Project No. I-4800-32
March, 1997

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APPENDIX A. DESCRIPTION OF THE SRC TEST METHOD

1 INTRODUCTION TO THE PROJECT

The introduction of the RFP states:

> "Most of the high-rise residential building stock was built in the late 1960s and early 1970s. As it was neither particularly well built nor energy efficient, increasing operation cost and maintenance costs and normal repair and replacement cycles are now driving owners to consider retrofits to improve durability, energy efficiency and occupant comfort".

This statement defines a need for a holistic approach to renovation and retrofitting of Canada's building stock. To realize the full benefit of renovation, however, a number of system performance aspects must be considered at the same time, and an integrated systems approach must be taken.

The CMHC research RFP went a long way towards addressing the complexity of rehabilitation in a solid masonry building. It called for documentation of the strategy with describing details before and after rehabilitation, monitoring the indoor air quality, energy, and envelope performance. The owner of the particular building, located in Prince Albert, Saskatchewan, has decided that adding interior wood frame walls is the cheapest and most practical solution. He also decided to add stucco to the exterior of all sides of the building except that side facing the street.

This decision, although based on economic and aesthetic considerations, implied a number of technical consequences. First of all, the old masonry wall, until now exposed to room temperature through the whole year, will be exposed to the prevailing cold weather of the extreme Saskatchewan climate. More importantly, however, while a large temperature difference across the brick wall during the cold and rainy fall (and even during the thaw periods in winter) resulted in the strong movement of moisture towards the cold surface, in the absence of a thermal gradient acting on the clay bricks, the drying capability will be strongly reduced. In effect, moisture content in the outer layer of the brick will be much higher and the risk for freeze-thaw and salt spalling deterioration will be much more pronounced.

To counteract this phenomenon the external stucco finish is needed. This stucco, however, may need to be applied to all walls of the building. Whether leaving one wall not protected with the external stucco is acceptable or not must be decided on technical grounds. Perhaps, it may be possible to continue with the existing concept, perhaps the level of thermal insulation must be reduced on the wall where the protective stucco is not applied to retain sufficient drying capability of the wall. Such a decision requires knowledge of the following:

1. Local driving rain conditions in the specified urban mezzo-climate,
2. Air leakage characteristics of the existing wall,
3. Freeze-thaw resistance of the existing wall.

Whether or not the stucco must be used, whether or not specific moisture attributes of the proposed stucco (water retention and vapour transmission) must be determined prior to its application, will depend on the level of risk in long-term performance (durability) of the masonry.

It was apparent, however, that the building owner (who was also the builder) lacked the sophistication needed for assessment of durability and long-term effects created by the renovation decision. This is why the Saskatchewan Research Council (SRC), who identified the field of building rehabilitation and energy as one of SRC's key areas of technology support, joined forces with CMHC and provided additional funding to expand the strategy development aspects and broaden the scope of this project to include two parts:

- the work leading to the development of the field diagnostics necessary to assess the actual performance of the masonry system comes with funding from a strategic research fund of the Saskatchewan Research Council, namely $23,000.
- the work on monitoring the indoor air quality, energy, and envelope performance as described by the RFP document

The Saskatchewan Research Council believes that this approach of building a technology driven consortium involving federal and provincial governments, experts in research and leading consultants, provides a substantial improvement to the process of technology transfer in Canada.

2 SRC CONTRIBUTION TO THE PROJECT

The SRC staff visited the building and observed cracks and surface spalling. Such defects are not unusual for 75 year old brick. While the CMHC project was focussed on the renovation process and evaluation of the efficiency of different measures, the contribution from the Saskatchewan Research Council included an assessment of the exterior finish on the building.

The objectives were:

- to assess rain penetration capacity of the existing masonry wall,
- to establish if external stucco is needed for the improvement of moisture balance,
- to assess if the selected stucco is suitable and if it will perform adequately in the harsh climate of Northern Saskatchewan,
- how to ensure the proper bonding strength of the selected stucco?
- is the enhanced cracking resistance of the stucco required and where?

2.1 Evaluating rain penetration through the existing solid masonry walls

2.1.1 Introduction

This report describes application of the SRC test method (designation C1T, see Appendix A) for testing water penetration through external walls. This test method applies a large amount of water to the wall surface under conditions of prescribed air pressure difference across the wall. The penetration of water through the test specimen can be examined. If the water penetration takes place, conditions and period of exposure leading to such a failure are determined.

Testing apparatus used for simulating rain penetration under field conditions contains the following three components:

- water spray rack
- water penetration sensors
- differential air pressure box

This apparatus described above was used to determine actual water leakage of a brick wall in the apartment building in Prince Albert, SK.

2.1.2 Deviations from the test procedure

There were no deviations from the specified test procedure as described in Appendix A.

2.1.3 Selection of test site and preparation of apparatus

The location of the spray rack was determined by the access routes. The best access to the external wall was from the roof of the building and the most convenient place to remove internal parging of the existing masonry wall was on the third floor. Therefore the spray rack was located 4.7 m above the test area where the water penetration sensors and the differential air pressure box were installed. This large difference in elevation could have caused a significant delay in the water penetration. Therefore, the water spray with a nominal intensity of 12 $l/m^2/min$ was obtained with a water line pressure of 20 psi.

Actual field testing was done on August 28, 1996 when two BSB personnel travelled to Prince Albert to install water detectors. They were installed ½ brick depth into the wall from the interior and then this test area was covered with a differential air pressure box. The air pressure box was installed by 8:00 p.m. on August 28. The apparatus was left in place to allow caulking material to cure overnight. This caulking was used to help seal the box against the irregular surfaced wall for an airtight seal.

2.1.4 Water penetration test

The air was pumped out of the box with help of a small oscillating pump, connected through a variable voltage power supply. The voltage on the power supply line was adjusted in such a manner that a 10 Pa air pressure differential between the inside and outside of the box was obtained and maintained during the duration of the test.

A strip chart recorder was connected to the water detectors. A small voltage (1.5 v) was applied to the circuit for the moisture detectors. This system was designed in such a way that when water would penetrate the wall and wet the sensors, the circuit was complete and the chart recorder would indicate the presence of water.

Water spraying started at 8:35 a.m. on August 29. At the same time as the water spray was started on the exterior wall, a small negative pressure of 10 Pa was applied to the metal box to create air suction on the wall at this test area.

Inspection of the wall surface at the test location at 11:38 a.m. showed considerable water leakage within the building. Water was actually flowing through the wall above the differential air pressure box, i.e., in the area where no artificial[1] air pressure differences were created. Since a significant mass of water was puddling on the third floor of the building this test was terminated at 11:40 a.m.

Observations from the water penetration apparatus were equally revealing. Since the air pump was not adjusted during the test period to exhaust the same quantity of air, and the presence of water in the test area of the masonry wall had a significant air tightening effect of the wall, there was an increase of air pressure difference across the wall from 10 Pa to 20 Pa.

The chart recorder showed that water penetration occurred 54 minutes after initiating the water spray on the exterior of the masonry wall.

2.1.5 Interpretation of results

Water detectors were activated within 54 minutes from the start of water being sprayed onto the exterior wall. One may also ask the question, why was there no complaint about water penetration to date? The answer is, perhaps, self evident. Two factors must be considered:

- the building shell has been very leaky,
- the internal stucco, applied on wood lath, provided a drainage plane and path to the foundation and the basement (unused) space.

In other words, there was a second line of defense that removed the effect of water penetration from the habitable space to the lesser part of the building, that luckily enough was not water sensitive.

---

[1] One may assume that a small air pressure difference was created by the wind and temperature differences between sunny and shaded portions of the building and were sufficient to cause the rain penetration through the cracks in this wall.

Now, during the course of renovation when the wood frame construction is to be installed in the basement space and walls are to be provided with air and vapor barrier systems, this very dismal moisture performance and extremely high risk of water penetration through the masonry walls requires serious consideration.

2.2 Evaluating bond between a proposed stucco and the existing masonry walls

2.2.1 Introduction

This report describes the application of an ad-hoc test method developed at SRC to examine the bond of a base coat of stucco to the existing masonry substrate. This test method uses an accelerated water ingress of the test specimen either followed by an oven drying (at 40°C) or no drying at all. Testing was performed on either wet or dry material to establish a comparative base of development of mortar strength at the bond strength at failure in the mortar brick interface. The wet tests were performed mainly because of the time limitations to observe the development of a mortar strength.

The following report presents the results obtained on the dry bricks used from the building only.

2.2.2 Material description

The base coat of stucco was applied on the masonry surface either primed with an adhesive (a polyvinyl acetate emulsion) or to the surface without a primer. A base coat of stucco mix consisted of 6 parts sand, 2 parts standard Portland cement, 1 part lime, 4 - 4.5 litres of water and ½ cup of fibre reinforcement. The thickness of the base coat stucco varied from 3 to 4 mm.

Five clay bricks were primed and covered with the base (scratch) coat and five bricks were covered with the base coat without the surface priming. Each brick was then cut into 5 pieces, a total of 25 specimens of each kind. The mounting brackets used for the tensile strength testing were attached with two component epoxy resin to the base coat.

2.2.3 Test results

Testing was performed with an Instron universal testing machine, and the results are shown below.

Table 1. Bond strength of stucco base coat

Sample number	Material batch	Surface priming	Specimen age, days	Period of accelerated water ingress, days	Bond strength, MPa
1-1	1	yes	16	5	0.6089
1-4	1	yes	15	4	1.391
2-2	1	yes	15	4	1.093
2-4	1	yes	16	5	1.135
3-1	2	yes	7	1	1.301
3-2	2	yes	9	3	1.357
6-1	2	no	9	1	1.378
6-3	2	no	13	5	0.519
6-4	2	no	13	5	0.392
7-3	2	no	13	5	1.278
7-5	2	no	13	5	0.421
8-2	2	no	13	5	0.291

2.2.4 Interpretation of results

The results shown above indicate no discrimination with regard to the brick surface treatment as far as the maximum bond strength is concerned. The base coat of stucco applied to the same masonry substrate shows the same maximum bond strength of approximately 1.3 MPa. This level was attained by three primed specimens (coded 1-4, 3-1, and 3-2) as well as by two untreated specimens (6-1, 7-3).

The above results are, however, quite clear with regard to the bond strength variability. Only specimens amongst those treated with the surface adhesive (code 1-1) fell below 50% of the maximum bond, while four untreated specimens fell below this level and three of them fell below the 33% level.

The need for surface primer is therefore clearly established. It is recommended not to improve the bond strength but to reduce the probability of weak spots, leading to debonding and a progressive delamination of the stucco from the clay brick surface. Therefore, the primer was used in the building.

2.3 Evaluating cracking propensity of base coat of stucco

2.3.1 Introduction

This report describes the application of ad-hoc test method developed at SRC to examine the cracking propensity of the base coat of stucco. This test method uses a cycle of accelerated water ingress followed by the surface heating. The latter not only dries the stucco but also creates significant thermal and hygric stresses.

Delamination and cracking caused by thermal shock and thermal stresses acting on the interface between stucco and the substrate were observed.

The apparatus used for testing of the cracking propensity of the base coat of stucco contains two components:

- water immersion chamber equipped with the capability to induce a controlled level of vacuum
- infra-red (IR) lamps for surface heating equipped with the capability to maintain the prescribed surface temperature

This apparatus described above was used to determine response of the base coat of the stucco proposed for renovation of the solid masonry wall in the apartment building in Prince Albert, SK.

2.3.2 Material description

The base coat of stucco was applied on the surface primed with an adhesive (a polyvinyl acetate emulsion). A base coat of stucco mix consisted of 6 parts sand, 2 parts standard Portland cement, 1 part lime, 4 - 4.5 litres of water and ½ cup of fibre reinforcement.

For the purpose of testing, this stucco was applied on-site, by the contractor, on 19 mm thick wood plank, primed with adhesive. The dimensions of specimens were approximately 200 mm x 250 mm. The thickness of the base coat stucco varied from 3 to 4 mm.

2.3.3 Testing

Testing was initiated on September 9 with three specimens (code 1, 2 and 3). Two additional specimens (Code 4 and 5) were added to the immersion tank on September 11. Two cycles of gradual air pressure reduction to approximately 500 Pa and recovery to 100 kPa over 5 - 8 hours period were applied to specimens 1 , 2 and 3. Only one such cycle was applied to specimens 4 and 5.

Specimens 1, 2, and 3 were exposed to IR lamps for one day. After room exposure during the weekend, the IR exposure was repeated for another day. Specimens 4 and 5 were exposed to longer periods of uninterrupted water immersion (4 days) followed by 1 day of the IR exposure.

There was, however, no significant difference between results obtained on both series of tests. The same pattern of longitudinal cracks, 30 mm to 40 mm apart each from the other, was observed on all tested specimens.

The main purpose of using the wood substrate was its dimensional instability (warping) during the one-sided wetting and drying process. During the priming, preceding the stucco application, there was a slight concave deformation. This deformation disappeared completely during the moisture ingress stage (fibre relaxation). Then, heating of the stucco surface resulted in the convex curvature, with an arch as high as 6 mm on 200 mm wide specimen.

2.3.4 Interpretation of results

An ad-hoc SRC test method was used to examine cracking propensity of the base coat of stucco, accelerate the weathering process of the material and permit assessing its long-term performance. This test yielded a significant thermal and hygric stress.

Even though the delamination and cracking caused by thermal shock and thermal stresses acting on the interface between the stucco and the substrate can not be quantified (i.e, we do not know whether this procedure corresponds to two or ten years of aging and weathering) the observations permit the selection of appropriate safety measures.

The following measures were therefore recommended[2] for the stucco applied on the Prince Albert building:

- use "weldbond" admixture in all applications of the base coat of the stucco
- make a schematic drawing of all major cracks in the masonry (they were mostly in vertical lines starting at the place where the window sill plate ends indicating moisture origin in the damage)
- immediately after applying the scratch coat, roll into the scratch coat about 20 cm (8 inch) wide strip of the fibreglass mesh used for reinforcement of the External Insulation Finishing System (EIFS) stucco applications
- as previously requested, make each day's work to be completed from one expansion joint to another (none of the expansion joints were allowed to be closer than 30 cm (1 ft) from the window sill plate end) and possibly as far as 60 cm (2 ft)
- as discussed later, an expanded metal lath was recommended as a reinforcing strip around all windows.

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[2] See fax from SRC to Duncan Hill, CMHC, September 18, 1996

3 TECHNICAL INPUT INTO THE CONSTRUCTION PROCESS

3.1 Characterization of existing conditions, field checks, and technical advice

Upon the awarding of the contract, the SRC project team met in Prince Albert (PA) with the building owners, CMHC representatives, the local project manager (Prakesh Engineering), the design team, and contractors to discuss the project and to define roles and responsibilities. Communication lines were established and since this meeting all information, including that related to SRC contribution to the project, was going through the project CMHC National Office (project manager).

Subsequently SRC paid a few visits to PA and had a few meetings with involved parties to review issues as they were emerging during the construction period. These issues included the following:

- placement of the exhaust grills and ducts and review of the mechanical ventilation design,
- adding insulation and moisture control measures around floor beams that penetrate into the external wall,
- issues related to selection and application of the stucco and control joint, see section 2.3.4,
- selected wall details and the wall/window interface in particular (see later text),
- continuity of air and moisture barriers, particularly those around windows and wall/floor junction,
- use of foam or polyethylene as means of moisture control around perimeter joists,
- need for resilient channels to improve the STC rating,
- trouble shooting when reviewing the architectural and mechanical drawings.

Material samples of the brick and mortar were obtained and tested at SRC. SRC forwarded them to the CMHC National Office for further testing.

A specific concern in the rehabilitation of old masonry walls, which inevitably have a large air infiltration, is improvement of the air barrier performance. To this end, two parallel measures were used:

- external stucco, which, when placed on masonry is known to retain air tightness over long-term service period
- polyethylene (PE) air/vapour barrier

External stucco on masonry substrate was proven by several field studies, for instance CMHC sponsored field study published by Garry Proskiw in the ASTM STP 1225 and updated in the upcoming issue of the Journal of Thermal Insulation and Thermal Envelopes (April 1997).

The usual concern when using the PE sheets as the air barrier is the capability to withstand the wind loads (see NRC/CMHC research on air tightness of different air barrier systems). In the discussed case the wind loads will be mainly carried by the stucco (with support of masonry) and the PE sheets can perform as air / vapour barrier, providing that the wall / window interface is properly designed.

The wall / window interface was discussed and modified several times until the final solution was developed for this PA apartment building. Figure 1 shows the window jamb detail.

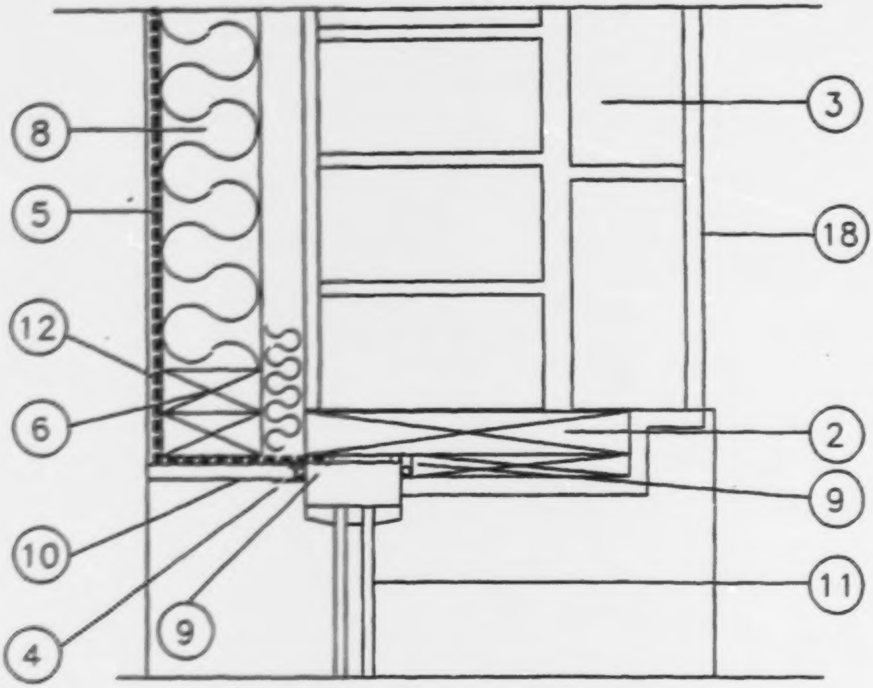

Figure 1. Window jamb detail from the modified drawing of Prakash Engineering for Karcher apartment building in Price Albert. The indoor space is on the left side of the drawing. The numbers from the left top represent: (8) is the glass fibre batt insulation, (5) is the 12.7 mm thick gypsum board, (12) is the 6 mil air /vapour barrier, (6) is the new wood framing, (10) is the foil-backed 12.7 mm gypsum (observe the difference between this gypsum board and (5) used elsewhere), (4) is the support for gypsum board return, (9) is the continuous caulking bead (see later text), (11) is the vinyl window, (2) is the existing wood framing, (18) is the stucco finish, and (3) is the existing solid masonry wall.

The double application of the calking compound shown in the jamb detail (Figure 1) is difficult to understand without an explanation of the work sequence. First a bead of caulking was applied on the window frame, than the window was inserted and pressed against the newly added wood blocking (9) and then the second bead of caulking was applied. The external caulking bead functions as a filler equalizing the gaps as they vary around the window perimeter. The internal caulking bead, which is exposed to room temperature and wall reduced movements (observe the presence of an air gap surrounding the inserted window) forms a real seal.

The next level of security is achieved by drawing the PE sheet under the foil-backed drywall return. To examine the quality of the installation of the PE air/vapour barrier, SRC conducted an in-situ test.

3.2 Room pressure test to examine quality of PE air/vapour barrier installation

3.2.1 Background

The interior framing, insulation, and vapour barrier have been installed throughout the apartment building as of October 24, 1996. A company from Prince Albert (Hubbel Insulating) with experience with the R2000 program installed the vapour barrier. CGSB approved polyethylene and acoustical sealant were used. A generally thorough job had been done on the vapour barrier installation in the building with care taken at all interfaces and joints.

The building has a number of interesting air tightness challenges with one feature being shiplap boards at the floor levels which extend out past the vapour barrier. Shrinkage between the shiplap boards results in a slot between each of the boards. This problem was addressed by filling the slots with acoustical sealant.

Only a short period was available to test the vapour barrier. Because the building was not sufficiently sealed to do an entire building air test with a blower door, one room in the building was tested. The room was on level three, on the west side of the building. Figure 2 presents a plan view of the room tested.

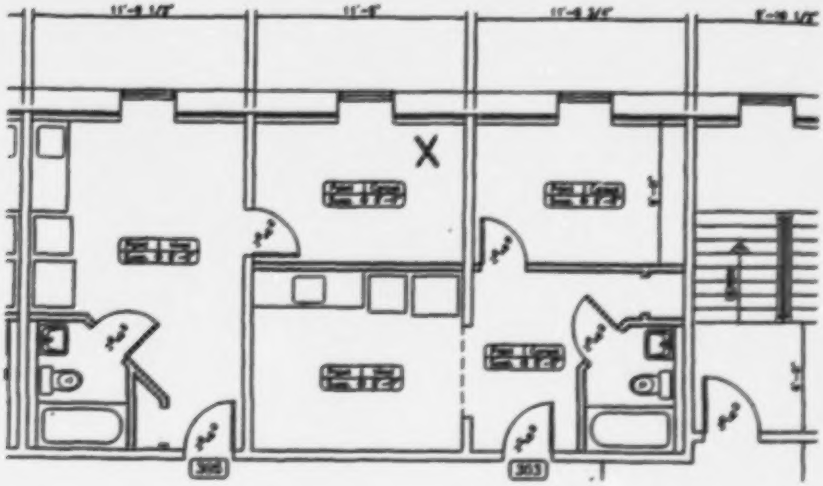

Figure 2. Plan view of the apartment building. The tested room is marked with the letter X.

In order to separate the room from the rest of the building and enclose it on all sides except for the tested wall, a temporary layer of 4 mil polyethylene was installed on the inner surfaces of the wall studs and the ceiling. Two inch wide plywood battens were placed on the walls and ceiling to temporarily hold the polyethylene in place.

3.2.2 Methodology

1. Bedroom of suite 305 on level three of the building on the west side was chosen for the test.
2. The interior of this room except the floor was lined with a temporary layer of polyethylene. The polyethylene was stapled and all lap joints of the polyethylene were covered with strips of plywood to temporarily cover the joints.
3. A Minneapolis Blower Door(TM) was installed in the doorway to the room to provide either a positive or negative pressure to the room.
4. Upon completion of the installation of the temporary polyethylene, the blower door fan with the attached pressure differential flow measuring and pressure difference equipment was turned on. Because the polyethylene was installed with staples and battens the pressure used was limited to 20 Pa on suction, though one test with 30 Pa positive pressure was also performed. Using a smoke pencil, all of the major potential sites for air leakage were checked.
5. The test was witnessed by: the owners of the building, Rick Strauss and Glen Olsen; Alison Rolph from Prakash Engineering; Mark Bomberg, Rob Dumont, and Larry Snodgrass from the Building Systems Branch of the Saskatchewan Research Council.

3.2.3 Results

1. The air tightness of the vapour barrier was good. All of the overlapping seams were checked for air leakage and none was found.
2. The window was found to be generally low in leakage.
3. The exterior stucco on the building seems to provide a relatively good air seal. The gap between the edge of the window and the vapour barrier on the wall did not exhibit a large amount of air flow.
4. A very slight amount of air leakage was found in the one electrical box located on the exterior wall. It is believed that although a plastic box was used around the electrical box and the plastic box sealed to the wall vapour barrier, the wire penetration through the box was not caulked which resulted in a small amount of air leakage.
5. One area which needs upgrading before the gypsum board is installed is the cross blocking on floor joists at the ceiling height. The polyethylene had to be cut around the cross blocking and this had not been sealed. This will require remedial action. The attachment of the vapour barrier to the large beams penetrating the outside wall was satisfactory.
6. The vapour barrier installation between the vapour barrier on the wall and the window frame was not complete. The air sealing technique to be used requires the use of foil backed gypsum board and caulking. This had not been installed.

3.2.4 Conclusions

1. The vapour barrier installation was found to be of a high quality. The contractor has extensive experience in the R2000 program. The methods used were similar to the methods used in a typical R2000 house.
2. Some remedial work is required at the 2 x 2 cross bridging on the ceiling/floor joists. There is only one location where this is required in the suite tested. Other locations in the building need to be fixed the same way as suite 305 bedroom.
3. Foam gaskets (CSA approved) should be placed over each of the electrical outlet boxes on the outside walls.

Note: It is recommended that in future work of this type, when the heat is on in the building and there is a temperature difference of more than 10°C between inside and outside, that a thermal camera be considered for the diagnostic work of checking the air-vapour barrier along with smoke pencils.

3.3 Energy use prior to rehabilitation

The energy records for natural gas consumption for the building were received from Sask Energy, the natural gas utility in Saskatchewan. Readings from the period July 1994 to June 1996 were available.

The building has had a very irregular pattern of meter readings. For example, during the last 12 months of readings, only four actual readings were made, the rest were estimates. As a consequence, it has not been possible to provide a relationship between natural gas consumption for space heating and the exterior heating degree days.

The annual natural gas consumption from June 1995 to June 1996 amounted to 1433.8 million Btu. This was for a period of 371 days. The previous year from July 1994 until July 1995, the total consumption amounted to 1453.8 million Btu for a period of 365 days. Based on these two years of meter readings, the natural gas consumption of the building was quite repeatable over the two year period. The total square footage of the building including all four floors amounts to 1681 square metres (m^2). The annual consumption for the two years normalized by the floor area and a 365 day time interval amounted to 885 megajoules per m^2 per year for the 1995-96 period and 912 megajoules per m^2 per year for the 1994-95 period.

4. BUILDING ENVELOPE, INDOOR AIR QUALITY AND ENERGY CONSUMPTION MONITORING

4.1 Approach to monitoring

SRC's experience with field performance monitoring (e.g., the Advanced House in Saskatoon, low-energy multi-family project in Regina, and other projects) can be summarized as follows: collecting data over short periods is suitable for benchmarking of facilities, however, this may not be sufficient for the evaluation of efficiency of renovation and thermal upgrades. Since the normalization of energy consumption data (usually done with degree-days and outdoor temperature) is valid only on the statistical basis, it requires a prolonged period of monitoring. Therefore, all energy related measurements need to be performed on a continuum basis. In practice at least two months in the winter period and one month in each season: spring, summer and fall should be used for evaluation of the annual performance. These measurements include indoor and outdoor air temperatures, thermal resistance of the walls, air pressure differential between the frame wall cavity and weather data.

SRC will collect data continuously using a multi-channel data logger. This data will be download bi-weekly. Furthermore, SRC does not measure pressure but pressure differences, the latter for the purpose of reducing the measurement noise. Data will be screened (using SRC designed software) on a monthly basis. This is the most precise and reliable method. Two modes of thermal analysis will be used, a transient analysis of heat flux (such as HFC method, used by NRC in measuring transient thermal performance of cellular plastic foams exposed on experimental roofs or ORNL software for non-linear regression analysis used in a similar project) and use of heat flow transducers.

4.2 Monitoring performance of building envelope

Six locations on the exterior walls will be monitored. Monitoring periods include a minimum two months in winter, one month each in the fall, summer, and spring seasons. Based on the prevailing wind conditions, namely westerly for summer, fall and early winter, easterly for February to June; the northwest and southeast corners were selected for two monitoring sites each. The other monitoring sites are in the middle of east and west-facing walls and the north wall. The installation of the monitoring equipment has been performed while access was available and when scheduling did not conflict with the renovation.

Three of the four attributes of wall system performance requested in RFP, namely, air leakage control, rain penetration control, and the level of thermal resistance are measured continually. The fourth, vapour diffusion control, is considered of a small significance for the solid masonry walls that are provided with an internal parging. Furthermore, the presence of the 6 mil polyethylene in the wood frame wall added on the inside effectively eliminates this consideration from the project.

Table 2. Location of Wall Monitoring

Monitoring Locations		**Comments**
Northwest Corner	NW1	Level 1 mid height
North Wall	N4	Level 4 mid height
Northwest Corner	NW4	Level 4 mid height
Southeast Corner	SE4	Level 4 mid height
West Wall	W2	Level 2 mid height
East Wall	E3	Level 3 mid height

The following sections describe in more detail the monitoring equipment and protocol.

4.2.1 Air leakage control

Air leakage control, or air barrier performance as often called by NRC, will be addressed by performing the two following differential pressure measurements at the six wall locations mentioned in Table 2:

- air pressure differential between outdoor air and inner surface of the wall (cavity with glass fibre insulation) will be measured continuously by means of a differential pressure transducer connected to a data logger,
- air pressure differential between indoor and cavity outdoor air will also be measured and recorded continuously.

These measurements will be done using continuous data gathering on a two minute basis with recording hourly of averages on the data logger. The sensors chosen for this measurements are Dwyer differential pressure transmitters with a specified repeatability of 1% over a one year time interval. Sensors with a 0 to 250 Pascal range were chosen.

In this manner, we will measure the air barrier performance of the solid masonry and the external stucco over a long period of time. These measurements performed over the period of one year will permit a random check to see if the external stucco develops cracks and reduces its contribution to the air barrier performance of the whole system.

4.2.2 Rain penetration control

Rain penetration sensors designed and built at SRC and Wetness sensors (Duff) designed and built by Dr. Don Onysko were located at the six exterior wall monitoring stations to map rain penetration. These sensors are located at the six exterior wall locations mentioned above. These sensors will be read by the data logger at one minute intervals and the data stored hourly.

SRC's rain penetration sensors that were also used in tests described in section 2 of this report. The phenomenon used is the change in electrical resistivity of a filter paper between two copper conductors when liquid water contacts the surface.

4.2.3 Rain gauges

Rain gauges will be installed at the nearest parapet locations to the two corner monitoring sites (NW4 and SE4). These will be tipping bucket rain gauges connected to the data logger placed in the basement.

4.2.4 Weather station

The weather station will be mounted on the roof of the building. The weather station will include wind speed and direction, outdoor temperature, relative humidity, and precipitation.

4.2.5 Wetting patterns

A local consultant will be hired to visually record the wetting patterns following larger rainfalls. Elevation drawings will be provided and sketches will be done.

4.2.6 Wall cavity relative humidity

Relative humidity will be monitored continuously using relative humidity sensors at all six locations. The following relative humidity sensors will be used: Vaisala Humitter 50U; Accuracy ±3% over range 10% to 90% rh; stability of ±2% over 2 years.

4.2.7 Wall temperature and heat flux

Temperatures will be monitored by the use of type T thermocouples at six points in the cross section at the six monitoring stations on the exterior walls. These locations are:

1. Exterior of the stucco
2. Interface of the stucco and the existing masonry wall (placed before the stucco)
3. Interface of the existing masonry wall and the new wood framing
4. Drywall surface facing the insulation
5. Drywall surface facing the indoors
6. Indoor air temperature

All of these sensors will be monitored using the data logger at a five minute reading interval with hourly averages for each sensor stored on disk.

Heat flux will be monitored by using heat flux sensors made from calibrated, one inch thick EPS board placed behind the gypsum wallboard. A thermopile consisting of 6 type T junctions will be used to measure the temperature difference across the EPS board.

Field determination of the *thermal insulation performance index* is an addition to this project. Many people are questioning the validity of material properties measured on small, dry and often preselected, laboratory specimens to estimate the whole system thermal performance under field condition, without any correction for the service conditions. As shown in many field studies, the level of thermal resistance under field conditions may be quite different from that measured in the laboratory. Since the RFP (and rightly so) has identified six points of temperature measurements across the wall, SRC will use these measurements and transient HFC technique to measure simultaneously the overall thermal resistance and thermal insulation performance index.

4.2.8 Wood moisture content in ends of joists

The floor joists run in a north-south direction. The joists rest on brick on the outside walls. To check for potential moisture damage, moisture pins were located in the ends of three ceiling joists located at the north end on the 4th floor. These moisture pins will be read with the data logger on a 20 minute frequency and the averages stored hourly. A correlation will then be used to relate the resistance measured to the wood moisture content.

4.2.9 Placement of sensors in the solid masonry walls are shown in Figures 3 to 8

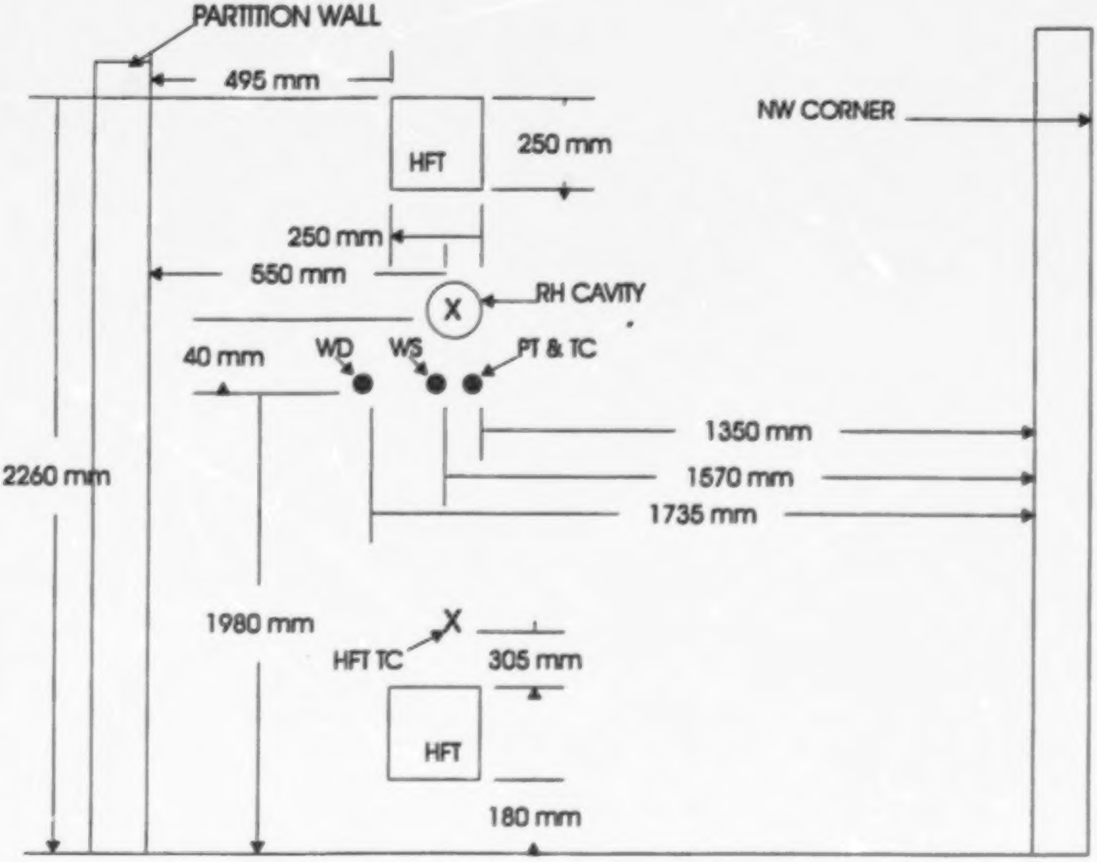
PARTITION WALL
495 mm
NW CORNER
HFT
250 mm
250 mm
550 mm
X
RH CAVITY
40 mm
WD
WS
PT & TC
1350 mm
1570 mm
1735 mm
2260 mm
1980 mm
X
HFT TC
305 mm
HFT
180 mm

Figure 3. Placement of sensors on the west wall, fourth floor, test location NW4 (all distances are shown in millimeters). Thermocouples are marked TC. Pressure taps, marked PT, are located on the inner surface of the drywall, on the inner brick surface (inside wall cavity) and a few millimeters into the outside air. WD is the Duff moisture sensor (calibrated wood) and WS is the SRC wetness sensor. Upper HFT code 439-80, lower code 439-78. Vaisala humitter 50A (R2120004) Note: When mounting the sensors the crew observed that there was no insulation behind the wood studs.

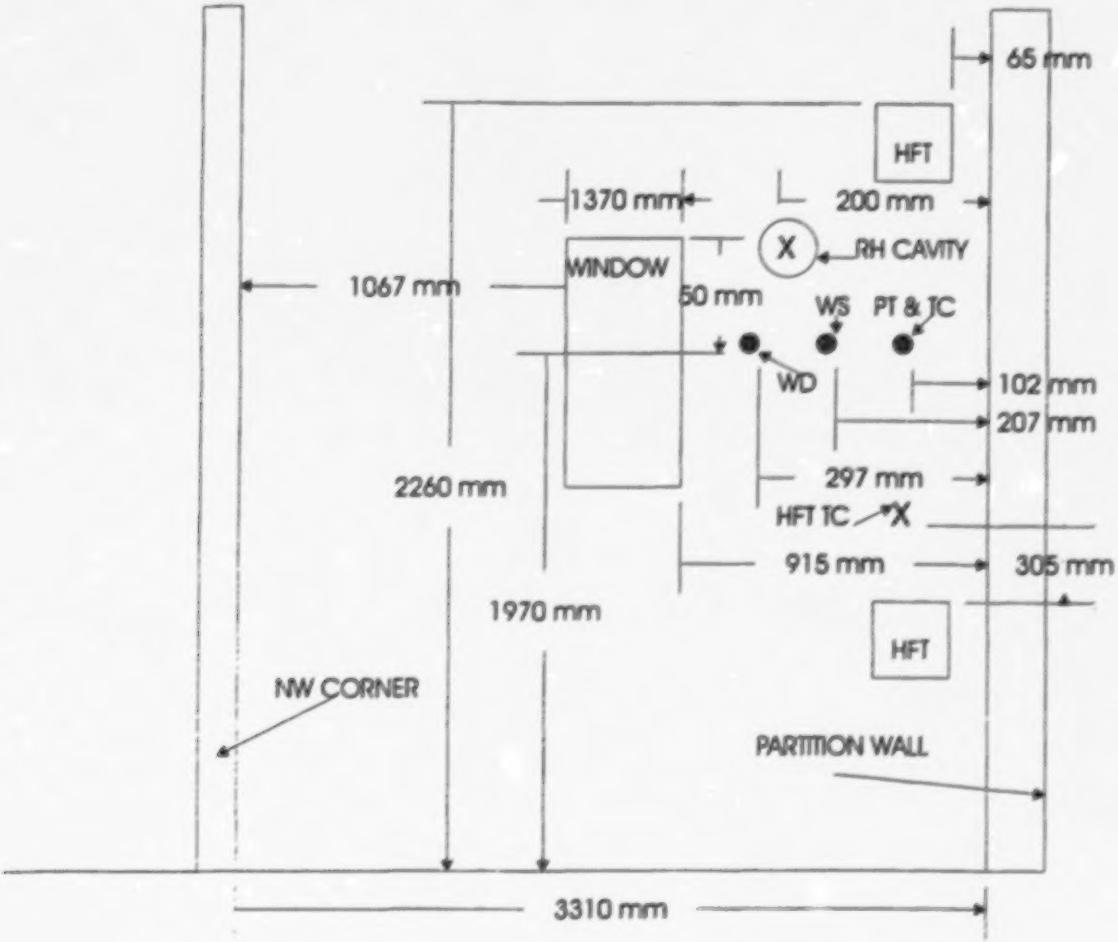
65 mm
HFT
1370 mm
200 mm
RH CAVITY
WINDOW
1067 mm
50 mm
WS
PT & TC
WD
102 mm
207 mm
297 mm
2260 mm
HFT TC
915 mm
305 mm
1970 mm
HFT
NW CORNER
PARTITION WALL
3310 mm

Figure 4. Placement of sensors on the north wall, fourth floor, test location N4. Thermocouples, marked TC, and pressure taps, marked PT, are located on the inner surface of the drywall, on the inner brick surface (inside wall cavity) and a few millimeters into the outside air. WD is the Duff moisture sensor, and WS is the SRC pressure sensor. Upper HFT code 439-81-2, lower code 439-87. Also Vaisala humitter 50A (R2120001). Note: When mounting the sensors the crew observed that there was no insulation behind the wood studs.

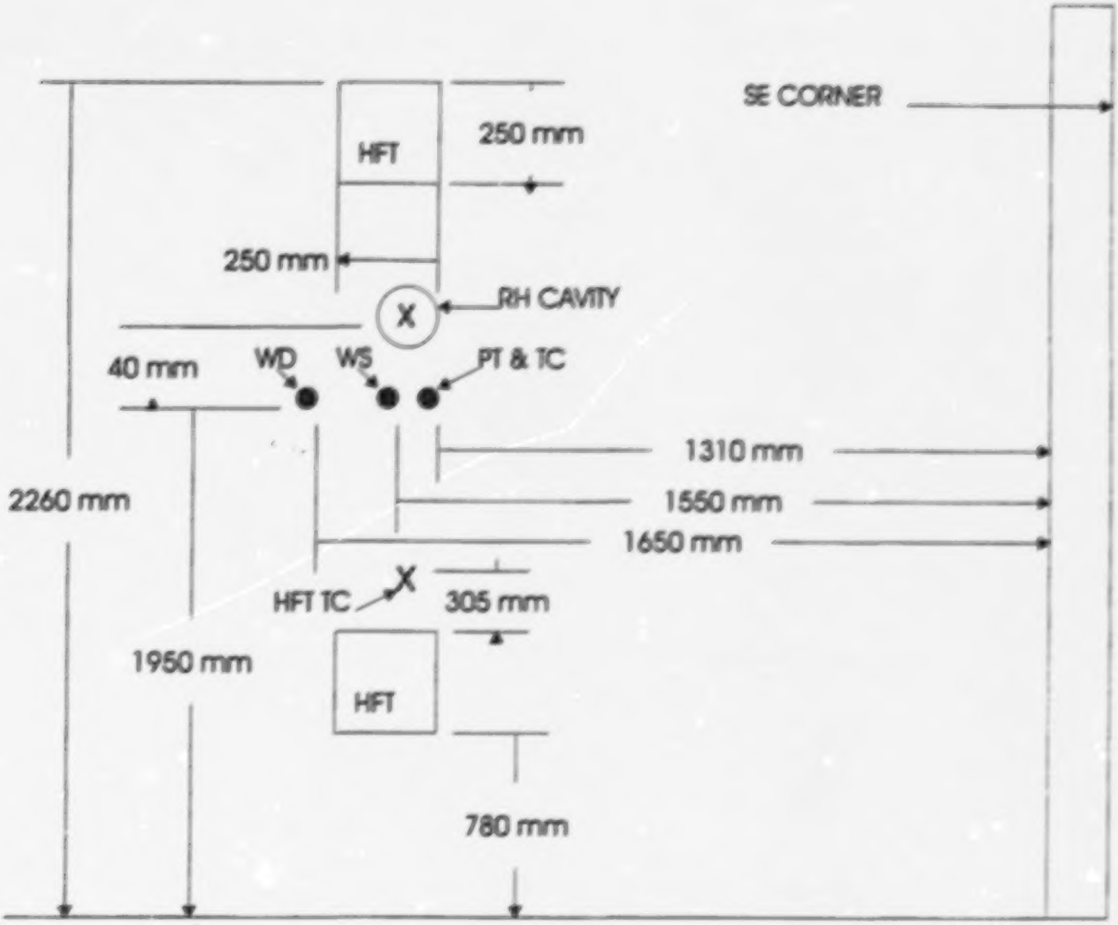
SE CORNER
HFT
250 mm
250 mm
RH CAVITY
40 mm
WD
WS
PT & TC
1310 mm
2260 mm
1550 mm
1650 mm
HFT TC
305 mm
1950 mm
HFT
780 mm

Figure 5. Placement of sensors on the east wall, fourth floor, close to the SE corner of the building, test location SE4. Thermocouples, marked TC, and pressure taps, marked PT, are located on the inner surface of the drywall, on the inner brick surface (inside wall cavity) and a few millimeters into the outside air. WD is the Duff moisture sensor, and WS is the SRC pressure sensor. Upper HFT code 439-86-2, lower code 439-86-1.

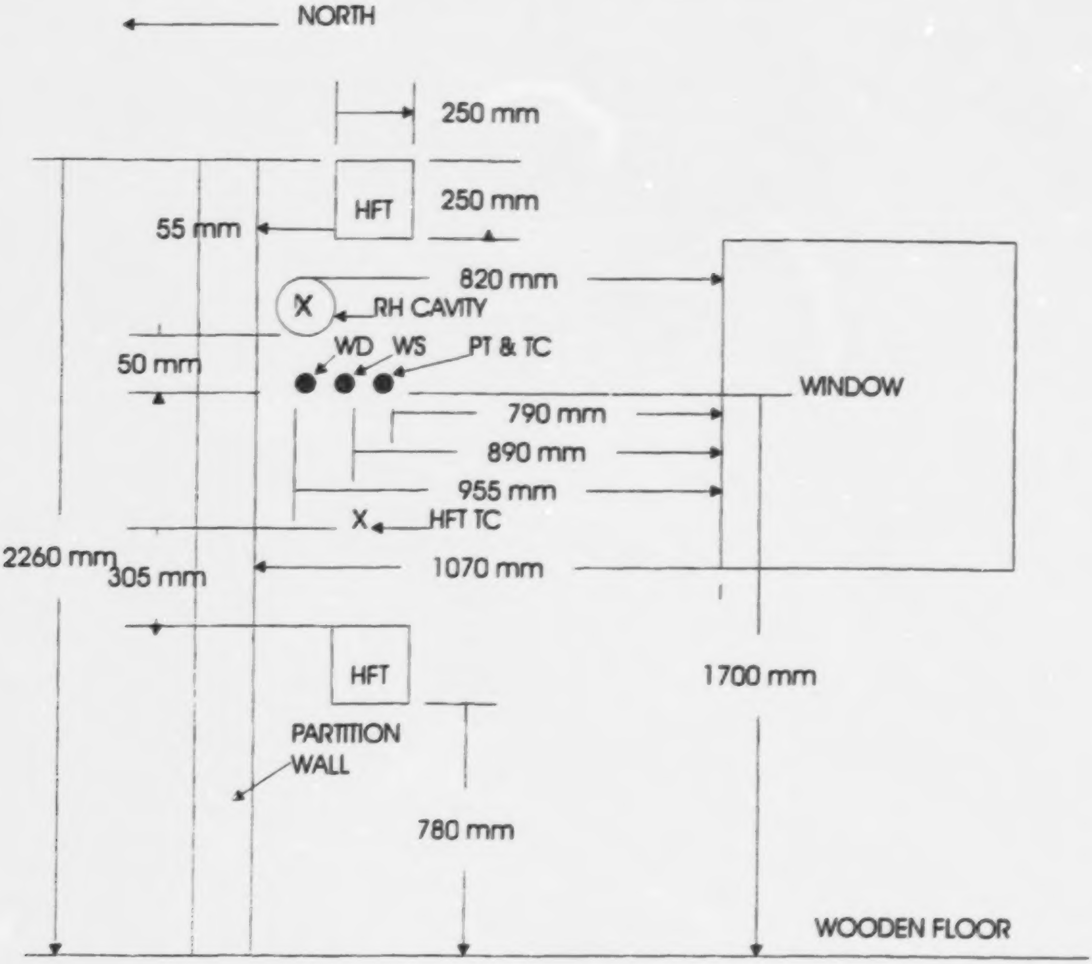
NORTH
250 mm
HFT
250 mm
55 mm
820 mm
RH CAVITY
WD
WS
PT & TC
50 mm
WINDOW
790 mm
890 mm
955 mm
HFT TC
2260 mm
305 mm
1070 mm
HFT
1700 mm
PARTITION WALL
780 mm
WOODEN FLOOR

Figure 6. Placement of sensors on the east wall, the third floor, test location E3. Thermocouples are marked TC, and pressure taps are marked PT. WD is the Duff moisture sensor, and WS is the SRC pressure sensor. Upper HFT code 439-77, lower code 439-83. Vaisala RH sensor number 2120016.

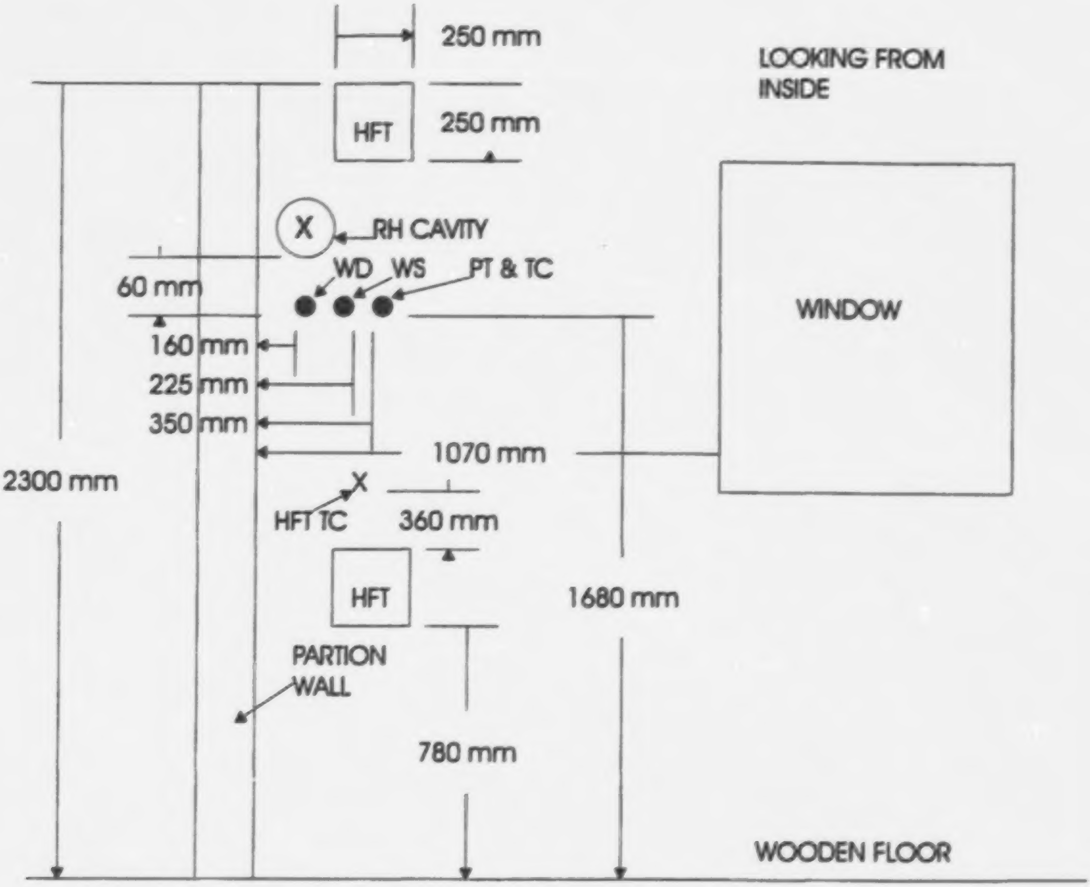
250 mm
LOOKING FROM INSIDE
HFT
250 mm
WINDOW
X
RH CAVITY
WD
WS
PT & TC
60 mm
160 mm
225 mm
350 mm
1070 mm
2300 mm
X
HFT TC
360 mm
HFT
1680 mm
PARTION WALL
780 mm
WOODEN FLOOR

Figure 7. Placement of sensors on the west wall, the second floor, test location W2. Thermocouples are marked TC, and pressure taps are marked PT. WD is the Duff moisture sensor, and WS is the SRC pressure sensor. Upper HFT code 439-84-2, lower code 439-84-1.

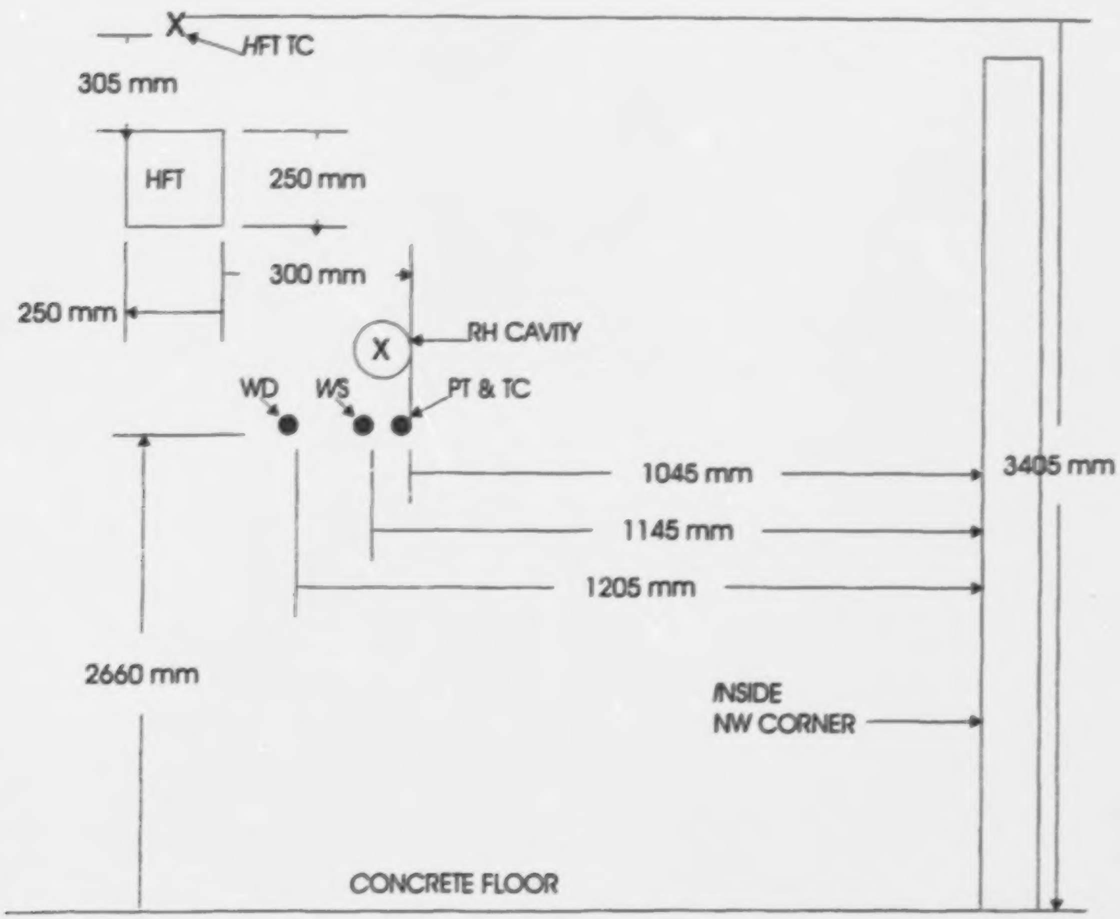
HFT TC
305 mm
HFT
250 mm
300 mm
250 mm
RH CAVITY
WD
WS
PT & TC
1045 mm
1145 mm
1205 mm
3405 mm
2660 mm
INSIDE
NW CORNER
CONCRETE FLOOR

Figure 8. Placement of sensors on the west wall, the first floor, close to the NW corner of the building, test location NW1. Thermocouples are marked TC, and pressure taps are marked PT. WD is the Duff moisture sensor, and WS is the SRC pressure sensor. HFT code is 439-21-1.

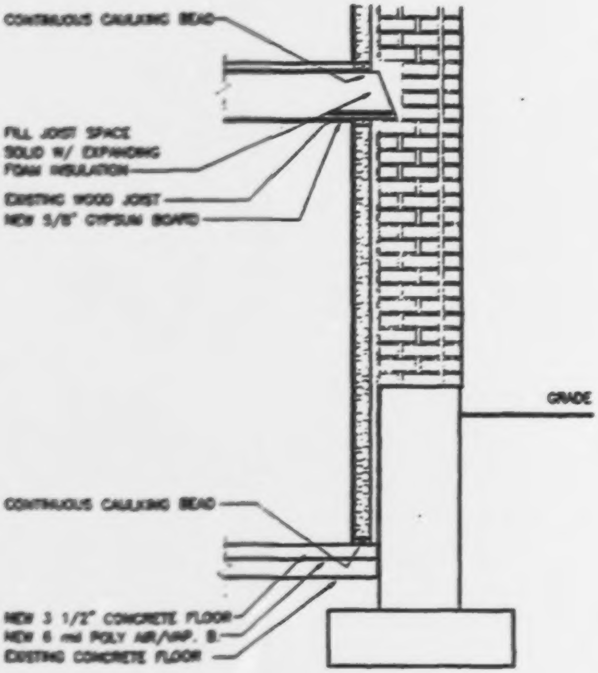
CONTINUOUS CAULKING BEAD
FILL JOIST SPACE SOLID W/ EXPANDING FOAM INSULATION
EXISTING WOOD JOIST
NEW 5/8" GYPSUM BOARD
GRADE
CONTINUOUS CAULKING BEAD
NEW 3 1/2" CONCRETE FLOOR
NEW 6 mil POLY AIR/VAP. B.
EXISTING CONCRETE FLOOR

Figure 9. A cross section of the solid masonry wall after rehabilitation.

4.3 Monitoring environmental conditions in selected spaces

4.3.1 Attic moisture

Wood moisture pins were placed in three locations in the attic space. These locations are:

1. In the roof joists at the north side of the building.
2. In the roof joists near the attic hatch.
3. In the roof joists near the chimney chase on the south side of the building.

These pins will be read on a 20 minute basis and stored hourly. An attic air temperature sensor was located in the space over the insulation in the middle of the attic. A Vaisala relative humidity sensor was also placed there. These two sensors will be read by the data logger at five minute intervals.

4.3.2 Building air leakage

Three tests will be conducted of the building air leakage:

a. Upon completion of the vapour barrier in the first suite [a test suite], a qualitative check was made in the suite identifying locations where air leakage could occur. Special attention was paid to all interfaces (walls, ceilings, and floors, windows, electrical fixtures, plumbing fixtures). All air leakage paths were noted and repaired, and the builder was on site to note how to correct these air leakage sites.

b. The above air leakage test was to be re-done on a second suite at the same stage of completion. This was not done.

c. Upon completion of the building, a whole building air leakage test will be performed using the CGSB residential test standard. While the building is under a negative pressure or positive pressure, a qualitative check will be made of leakage paths not identified in the previous tests. SRC has a calibrated blower door that was previously used on a similar-sized well-sealed apartment building. While the pressure test is underway, the data logger will be running, and will provide a steady-state measurement of the pressure drops in the six exterior wall locations. This test will give a quantitative measure the location of the air barrier within the walls.

4.3.3 Pressure mapping of suites

Following the commissioning of the ventilation air supply and exhaust system for the building, pressure mapping of the pressure differentials between the suites and the corridors will be done using a manual readout Air Neotronics digital differential pressure transducer. The test involves sliding a pressure tap under the door of each suite and measuring the pressure difference between the suite and the corridor. The readout device is accurate to 0.1 Pascal.

4.3.4 Relative humidity in the building

Because of the relatively high supply and exhaust flows per suite, namely 38 L/s (75 cfm), and the relatively low occupancy per suite (1 or 2 persons), it is expected that the relative humidity will be low in the building.

A duct-mounted relative humidity sensor and a thermocouple will be placed in the exhaust air duct in the corridor on the south end of the corridor on the 2nd level of the building. This humidity sensor will provide an approximate average of the relative humidity values in the suites on that floor. The sensor will be read continually on a one minute interval basis by the data logger.

4.3.5 Energy and water consumption

Energy and water consumption will be monitored manually with sub-metering. The following meters will be used:

Table 3. Natural gas, electricity and water meters

Metered Quantity	Type of Meter
Total natural gas	Utility meter
Space heating energy	Utility quality natural gas
Make-up air heating unit	Utility quality natural gas
Domestic hot water energy	Utility quality natural gas
Individual suite electricity	Utility meters
Common area electricity	Utility meter
Cold water consumption	Utility meter
Domestic hot water consumption	Utility quality meter

The space heating, overall energy, and water consumption will be monitored to compare the pre- and post-retrofit performance of the building. A computer model of the building will be developed first using the AUDIT-2000 software. The apartment building has no air conditioning, relatively small windows, and relatively similar internal gains throughout, and thus can be approximated by a single zone building. If however, the modelling software is not able to handle the building, the DOE 2.1 software will be used as an option.

4.4 Indoor Air Quality

Air quality indicators of carbon dioxide, relative humidity, air temperature, formaldehyde, and volatile organic compounds will be monitored in three suites approximately one month after completion. Monitoring will be continuous for the two week period. The following equipment will be used for the tests:

Table 4. Indoor air quality instrumentation

Sensor	Manufacturer	Type	% Accuracy
Carbon dioxide	Young Env. Systems	YES-204 NDIR	± 5% of reading
Relative humidity	Young Env. Systems	YES-204 Capacitance Sensor	± 4% of reading
Air Temperature	Young Env. Systems	Thermistor	± 2°C
Formaldehyde	AQRI	PF-1	± 15% in range of 0.025 to 1.0 ppm
Volatile Organic Compounds	3M	Badge	Not stated, Detection range of 0.1 to 50 mg/m^3

The three suites will be located at the NW and SE corners and on the west side. A questionnaire used with the Audit 2000 program will be used to document the potential sources of indoor air pollutants in the three suites. The results will be compared with the Canadian Residential Guidelines for indoor air quality.

4.5 List of sensors and monitoring equipment

Table 5. Sensors and monitoring equipment

Sensor Type	Location	Ownership
Pressure Transducers	6 exterior walls; 2 sensors /wall;	CMHC
Rain penetration Sensors; SRC	6 exterior walls; 1 sensor per location	Left in wall
Wetness sensors; Don Onysko	6 exterior walls; 1 sensor per location	Left in wall
Rain Gauges; tipping bucket	2 corners on roof (NW & SE)	CMHC
Weather: wind speed, T, RH, direction, precipitation	Roof	CMHC
RH; capacitance sensor	6 exterior walls; 1 sensor / wall	Left in wall
Temperature profiles; T thermocouples	6 exterior walls; 6 sensors per wall	Left in wall

Sensor Type	Location	Ownership
Heat flux transducers;	11 sensors in exterior walls	Left in wall
Wood moisture pins	3 joist ends in north wall	Left in wall
Wood moisture pins	3 in attic joists	Left in attic
Attic air temperature	thermocouple in attic	Left in attic
Attic relative humidity	in attic air space	CMHC
Suite/corridor pressure maps	in corridors	SRC
RH in exhaust air and temperature	end of corridor exhaust duct, 2nd floor	CMHC
Sensor Wiring	Various	Left in wall
Power supplies for transducers	Various	CMHC
Data Logger Sciemetrics	Boiler room	SRC Rental to project
Carbon dioxide	3 suites	CMHC
RH	3 suites	CMHC
Air temp	3 suites	CMHC
Formaldehyde; AQRI Sensor	3 suites	Disposable
VOC- 3M Badge	3 suites	Disposable

Cost of the sensors, supplies and instrumentation purchased for the PA project

Description of the item	$ Planned	$ Spent	Why different
Weather Station (Y.M. Young, etc.)	2,800	3,015	with rain gauge
Fabricate tower	0	630	
Data logger (Sciemetrics)	1,500	1,500	–
Computer Rental	1,000	1,000	–
Computer Software (Co-Pilot)	200	107	–
2 Rain Gauges (Texas Electronics)	840	840	–
6 Temperature Monitors (ACR)	4,914		no, price limits
3 RH/Temp. Cavity Monitors	2,964		no, price limits
6 RH monitors for walls	1,530	1,653	add attics

Description of the item	$ Planned	$ Spent	Why different
RH monitor for attic space	255	276	
6 RH/Temp Cavity Monitors	–		3,964
6 Wetness Sensors - SRC	300	300	
9 Wetness Sensors - DMO	300	321	–
1 IAQ Yes-204 Monitor/Sensor	2,650	for 1997	–
Formaldehyde sensors (AQRI) (6 @$150)	900	for 1997	–
VOC 3M Badge	600	for 1997	
1 Pressure Reference (Energy Conserv.)	1,020	for 1997	
12 Pressure Sensors	4,368	4,368	–
exhaust air, RH sensor	255	381	
Wiring, Tubing, (Thermocouple)	3,360	3,755	longer leads
Heat flux transducers (SRC)	300	300	
Photographic slide and colour photo film and processing charges	200		–
total for 1997	**5,170**		
total for 1996	**16,144**	**17,846**	
TOTAL	51,570		

5 CLOSING REMARKS FOR THIS INTERIM REPORT

The construction schedule and consequently the timetable of this project has been changed so many times that one must now assume that monitoring will only start at the beginning of spring (April 1997). The first set of results would then be expected in the mid summer.

APPENDIX A

APPENDIX A. DESCRIPTION OF THE SRC TEST METHOD

THIS TEST IS BASED ON: ASTM E 331 and E 514
BUILDING PERFORMANCE DESIGNATION: R1

Version 2.0

TEST TO DETERMINE WATER PENETRATION INTO OR THROUGH EXTERNAL WALLS

1. Introduction

1.1 Considerable damage to exterior walls of buildings can be caused by the penetration of rain water. To determine if rain water can penetrate into or through a test specimen " existing walls or mocked-up components", an apparatus is used to simulate rain and pressure difference conditions and register the presence of water in the test specimen.

1.2 Two ASTM methods: E 514 addresses water penetration and leakage through masonry and E331 through exterior windows, curtain walls, and doors by uniform static air pressure difference. While this SRC test uses the same test conditions, the SRC method is more demanding in the measuring techniques, for instance water penetration sensors and electronic recording are required instead of visual observations that are specified in the respective ASTM documents.

2. Scope, significance and use

2.1 The purpose of this test method is to determine if water penetrates into or through a test specimen under specified conditions of air pressure difference and simulated rain intensity.

2.2 This method can be applied to walls, windows, wall/window interfaces, and other components of the building envelope for which such an examination is needed under either laboratory or field conditions.

2.3 In the laboratory testing, a mock-up of components of the building envelope can be subjected to accelerated weathering and tested for water penetration.

2.4 Based on the results of this test, appropriate measures such as air tightness of the wall or drainage/ drying capabilities should be considered.

3. Referenced documents

ASTM E 331 Standard Test Method for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference

E 514 Standard Test Method for Water Penetration and Leakage Through Masonry

4. Summary of the test method

4.1 A large amount of water is applied to the specimen surface under conditions of significant air pressure difference across the wall. The time elapsed until water penetration takes place is recorded using water penetration sensors.

5. Apparatus

5.1 The basic apparatus consists of three main components:

- water spray rack
- water penetration sensors
- differential air pressure box

5.2 **The water spray rack** may be used to achieve complete water coverage over the 2.44 m width of the rack. The spray rack consists of 19 mm diameter, polyvinyl chloride (PVC) pipe sections and 8 (or 15) atomizing spray nozzles placed 0.23 m apart from one another. The spray rack is constructed to allow for the use of either the 8 (or 15) nozzle configuration. The water flow rate can be modified by regulating the pressure of water delivered to the spray rack and by changing the spray nozzle size.

5.3 Four adjustable spacer rods at each corner of the frame keep the framework away from the wall or test surface for a maximum distance of 0.38 m.

5.4 A water supply hose is attached by a threaded union to the bottom row of the frame at the centre tee fitting. The water supply hose to this frame has a shut off valve, pressure gauge, flow meter, and pressure regulator. The water feed line to this system can be either 19 mm or 12 mm garden hose.

5.5 **Water penetration sensor/sensors,** commercial such as Onysko or ones developed at SRC can be used. The SRC sensors are constructed of a plexiglass rod 107 mm long and 12 mm diameter. Ashless #40 filter paper is placed over the perforated circuit board, below the plastic disk and plastic locking ring. Lead wire (22 gauge) is soldered to the circuit board and connected to a recording device.

5.6 **A differential air pressure box,** is a lightweight, open-sided 0.5 m^2 (0.7 m x 0.7 m), metal box used to enclose the test area of the wall or mocked-up test assembly. The box is provided with two ports. One is used to exhaust air, creating air suction. The other serves to measure the air pressure difference across the wall. An air pump capable of exerting a minimum of 10 Pa suction is attached to the metal box at port 1. A low range manometer is attached to port 2.

6. Sampling or preparation of test specimens

6.1 Unless specified otherwise, one field location is to be selected at random. If a mock-up sample of a cladding system is built for testing, the test is performed in such a manner that at least two panel joints are tested.

7. Preparation of apparatus

7.1 The water spray rack is assembled in such a way that the water spray will cover a minimum 1 m^2 of wall area.

7.2 If a wall to be tested is brick, water penetration sensors are located inside the wall, at a one-half brick distance from the interior surface.

7.3 The water penetration sensors shall be attached to a recording device to determine the elapsed time before the presence of water is observed at the sensor location.

7.4 A differential air pressure box is placed in contact with the interior surface of the test wall. This box is sealed against the wall surface with weather stripping and caulking, to permit attachment to uneven surfaces.

8. Calibration

8.1 Prior to use, the spray rack must be calibrated to determine the flow rate of water. For practical purposes, minutes are used instead of seconds as a unit of time. Calibration is accomplished through the following operations:

1. Assemble the spray rack and measure the area of its spray range, in m^2.
2. Connect the water supply line to the spray rack.
3. Record the initial reading on the flow meter and the supply water pressure.
4. Open the valve on the spray rack supply line.
5. Record time when water flow starts.
6. Let water flow through the spray rack for at least five minutes.
7. Read and record water pressure just before the water flow is discontinued.
8. Shut off water flow and record time.
9. Record the final reading on the water flow meter.
10. Determine spraying period, in seconds, as a difference between (5) and (8).
11. Determine total volume of water, in litres, from the difference between the initial (3) and the final (9) meter readings.
12. Determine the rate of water spray per minute, a ratio of (11) and (10).
13. Determine the intensity of water spray flow (flow rate per unit time and area), L/min/m^2, a ratio of (12) and (1).

8.2 If the measured intensity of water spray differs more than 20% from the benchmark recommended for the water penetration test, modify the water pressure and repeat the calibration procedure.

9. Specimen conditioning

9.1 When a mock-up test is performed, conditioning of the specimen is to be proposed by the client. Unless specified otherwise, 24 hour storage under room conditions is deemed appropriate conditioning.

10. Test procedure

The test is performed using the same sequence of operations as for 8.1 calibration, plus:

1. Mount the water spray rack at the test location (test specimen).
2. Set the rack at the required distance from the test surface using the adjustable rods.
3. Install water penetration sensors at the required location on the inner surface to be tested.
4. Connect sensor leads to the recording device and turn recording device on.
5. Install differential pressure box on the inner surface of the area to be tested, making sure the box covers the area where the water penetration sensors are located.
6. Install the suction apparatus and differential pressure measuring device.
7. Apply suction to the test area to obtain the required pressure difference (recorded in Pa) across the tested specimen.
8. Follow steps 3 to 13 under calibration.

11. Report

11.1 Report the following information:

1. Time and place of the spray rack installation.
2. Details of the installation of the water penetration sensors.
3. Details of the installation of the air pressure box, method of air sealing used.
4. Setting on the water pressure line.
5. Nominal intensity of water spray.
6. Nominal air pressure difference across the wall.
7. Details of water penetration recording.
8. Time when water flow was initiated.
9. Time when water penetration was observed.

12. Precision and Bias[3]

12.1 This test method provides a qualitative evaluation only. Since the actual period and intensity of rain may vary, the actual air tightness of the wall at different locations is also strongly variable. The results of this test should be considered as comparative, or as a benchmark only.

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[3] Test developed by : Larry J. Snodgrass, A.Sc.T.
Checked by: Jerry T. Makohon, QA Supervisor
Approved by: Mark Bomberg, Ph.D., D.Sc.(Eng)

Last review: October 25, 1996

INTERIM REPORT #2

The Renovation of an Apartment Building with Solid Masonry Walls

for

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SRC Publication No.
I-4800-34-C-97
Project No. I-4800-32
September, 1997

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APPENDIX B - DATA LOGGER MONITORING SENSOR LIST

1 KARCHER INTERIM MONITORING REPORT #2

Monitoring equipment, which includes a Data Logger, Computer, and Modem was installed by July 30, 1997. The system was fully commissioned on August 15, 1997. A solar radiation sensor that was missing a resistor caused the solar radiation data to be faulty until corrected on August 15, 1997. The monitoring program was modified twice from Saskatoon after August 15, 1997, by using the modem. A total of 101 sensors are connected to the computer.

The monitoring computer is down loaded at least every week via telephone from Prince Albert. The modem works very well, and transfers files at 1,500 bytes/second. All sensor data is saved every 30 minutes. A daily file consists of 42 kilobytes of data.

Appendix A lists the scan intervals for the various sensors. Appendix B lists all the sensors installed.

Dr. Mark Bomberg has been supplied with a sample of the field data for the wall heat flow meters.

Alison Rolph, a technologist, has been contracted to take photos of the wetting patterns for the exterior walls of the building. She will also take bi-weekly utility meter readings. The only device not presently working is the domestic hot water flow meter. Rick Strauss, the owner, had installed it on the warm side of the hot water tank instead of on the cold supply side. The meter has not worked since August 7, 1997. Rick has said he will fix and move the meter to the cold side.

The building exhaust and supply air flows are to be balanced. Jim Moorhead was to remind Rick that there is funding for this.

2 RESULTS

Graphs of temperatures, pressures, RH, wetness, wind, and rainfall will be presented below.

A plot of outdoor air temperature is presented in Figure 1. The readings start at day 233 (August 21, 1997) and extend to September 28, 1997. The temperatures are the half-hour averages. The outdoor air temperature sensor is located on the roof in the weather shield. At day 255, the outdoor temperature fell considerably, recovering on day 263. The month of September has been on of the warmest on record. There is a gap in the data logging from day 237 to day 241. A programming change was responsible for this gap. Rainfall on the roof is presented in Figure 2. Rainfall in a half-hour period peaked at 2.3 mm on day 264.

Wind speed measured on the roof is presented in Figure 3. The peak average wind speed recorded was 6.7 m/sec on day 271.

The pressure difference across the brick wall at the second floor location is plotted in Figure 4. The peak pressure difference for a half-hour period amounted to 37 pascals.

The corresponding pressure drop across the stud wall is plotted in Figure 5. Most of the pressure drop across the total wall is occurring across the brick wall. The whole building pressure test found this to be the case as well. The indoor air temperature in the second floor exhaust duct is plotted in Figure 6. The indoor air temperature dropped with the exterior temperature drop on day 256. On day 262 the indoor air temperature rose with the rise in the exterior temperature.

The inside RH measured at the second floor exhaust duct is shown in Figure 7. As the building is being ventilated at a rage of approximately 75 cfm/suite, the interior RH tends to follow changes in the outdoor air temperature, particularly during rapidly falling outdoor air temperature. For instance, at day 256, the outdoor air temperature fell to almost 0°C, and the interior RH dropped about 10%. A plot of the attic ceiling joist moisture content is presented in Figure 8. Very little change in moisture content was measured over the time interval.

The brick wall wetness sensor moisture content is plotted in Figure 9. Daily cycles are evident on the graph. This sensor is located on the portion of the wall where the rain penetration test was performed in August of 1996.

The graphs (Figures 1 - 9) represent only a portion of the data gathered. The spreadsheet containing the data is being forwarded to Dr. Mark Bomberg for his analysis of heat flows, wall drying, etc.

3 WORK PLAN

1. Indoor air quality, RH, and $C0_2$ testing will be done on three suites in November or December, 1997 - whenever the NRCan Telaire units are available.
2. Data logging is scheduled to continue until Fall, 1998.
3. Meter readings and rainfall wetting patterns will continue until Fall, 1998.
4. The next monitoring report will be provided by December 31, 1997.

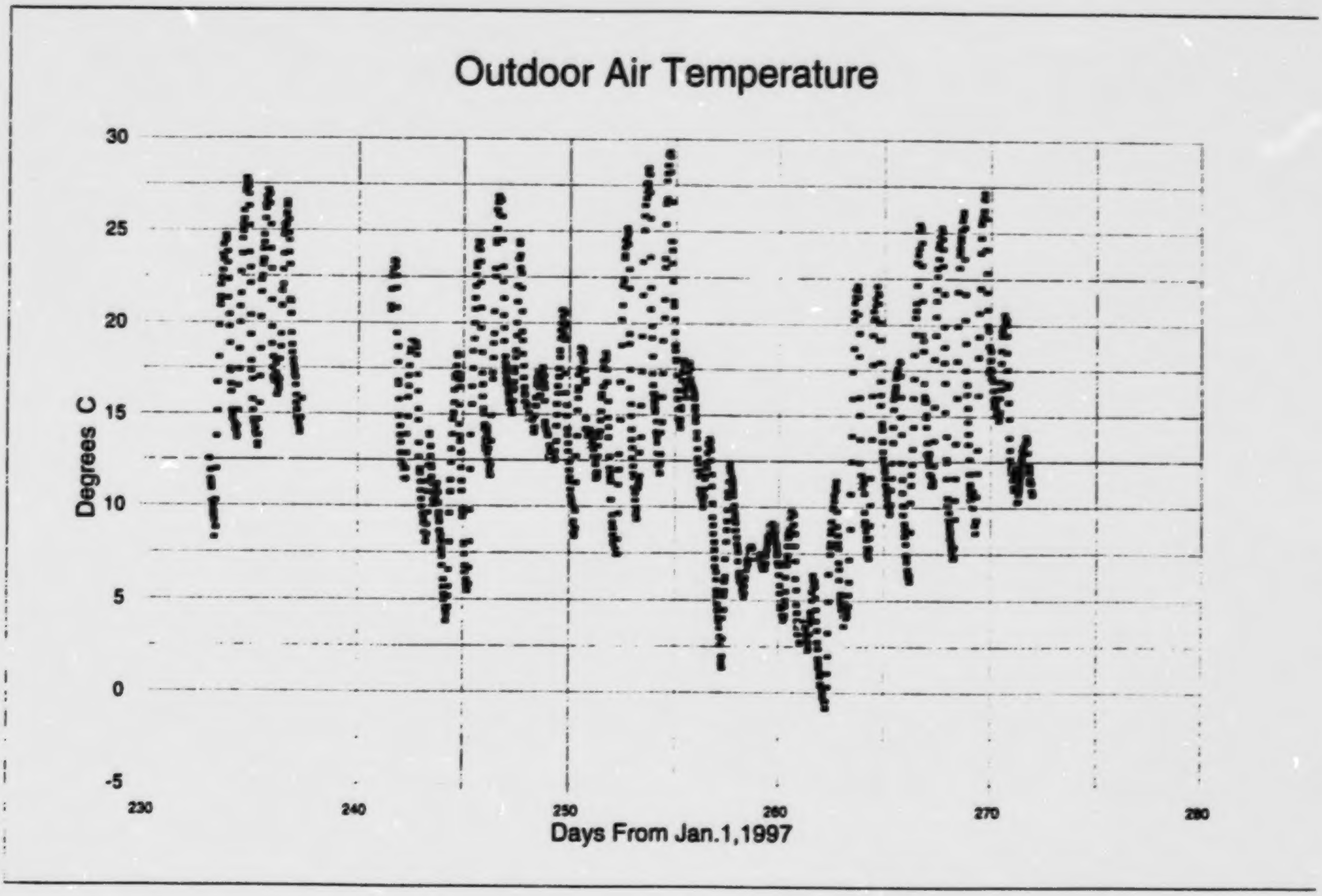

Figure 1. Outdoor Air Temperature

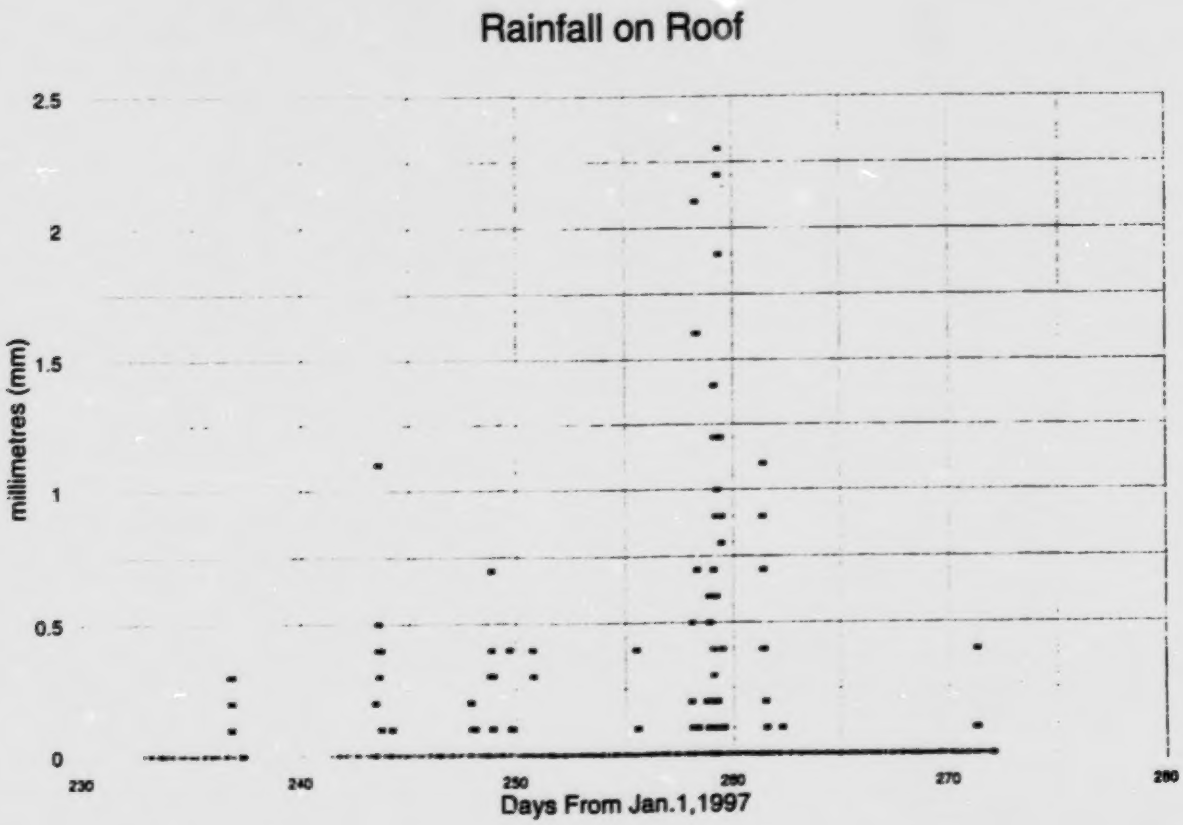

Figure 2. Rainfall

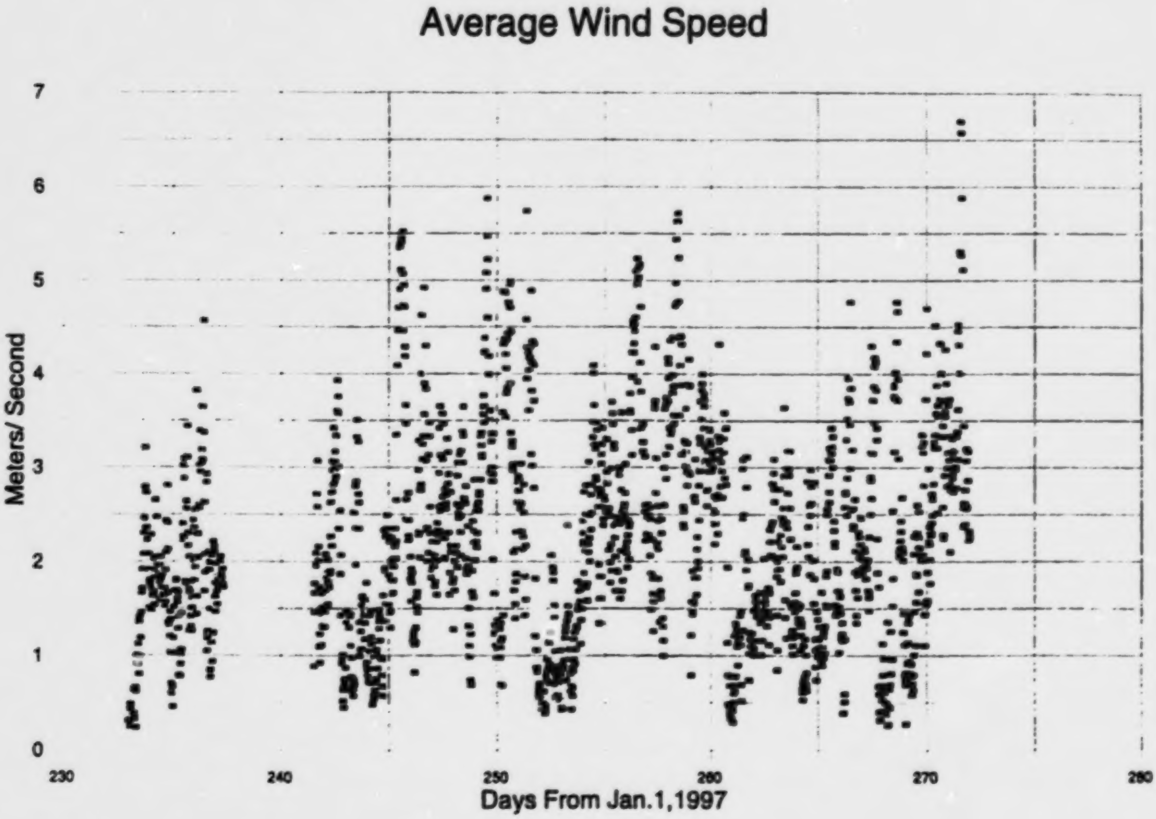

Figure 3. Wind Speed

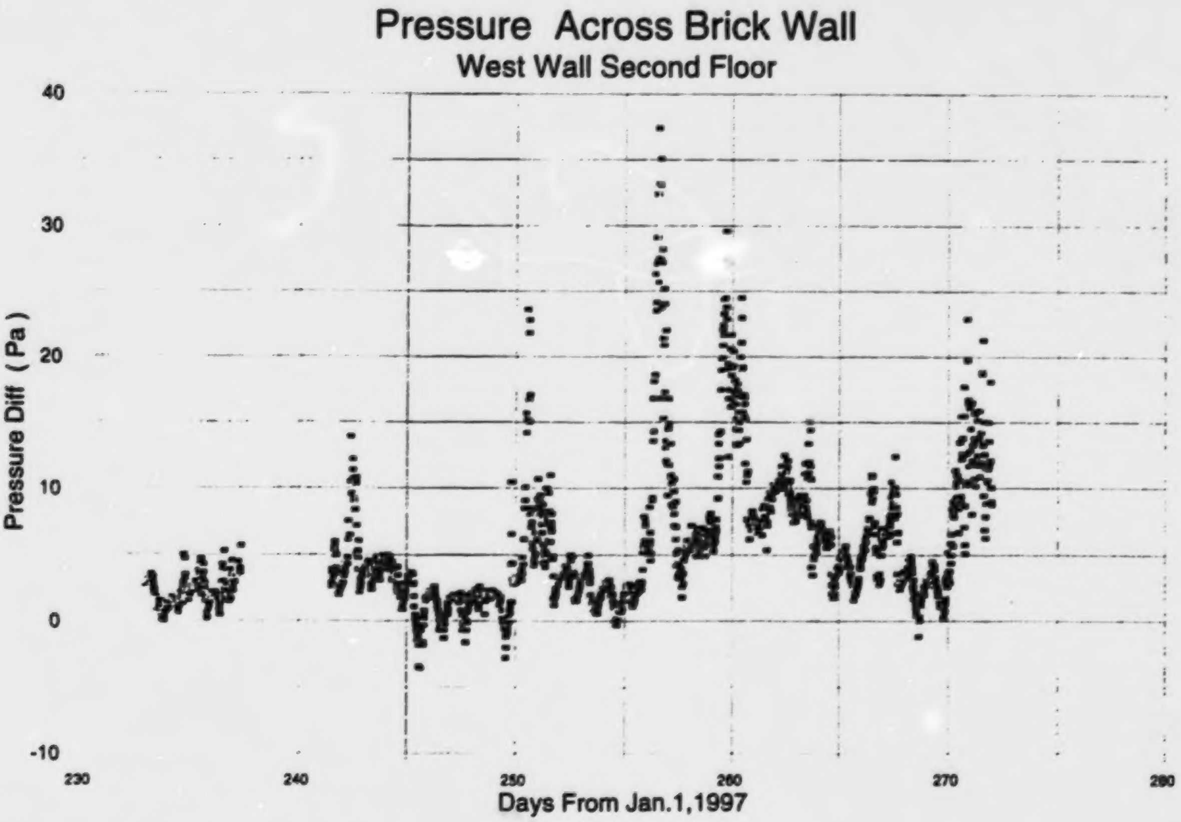

Figure 4. Pressure Across Brick Wall

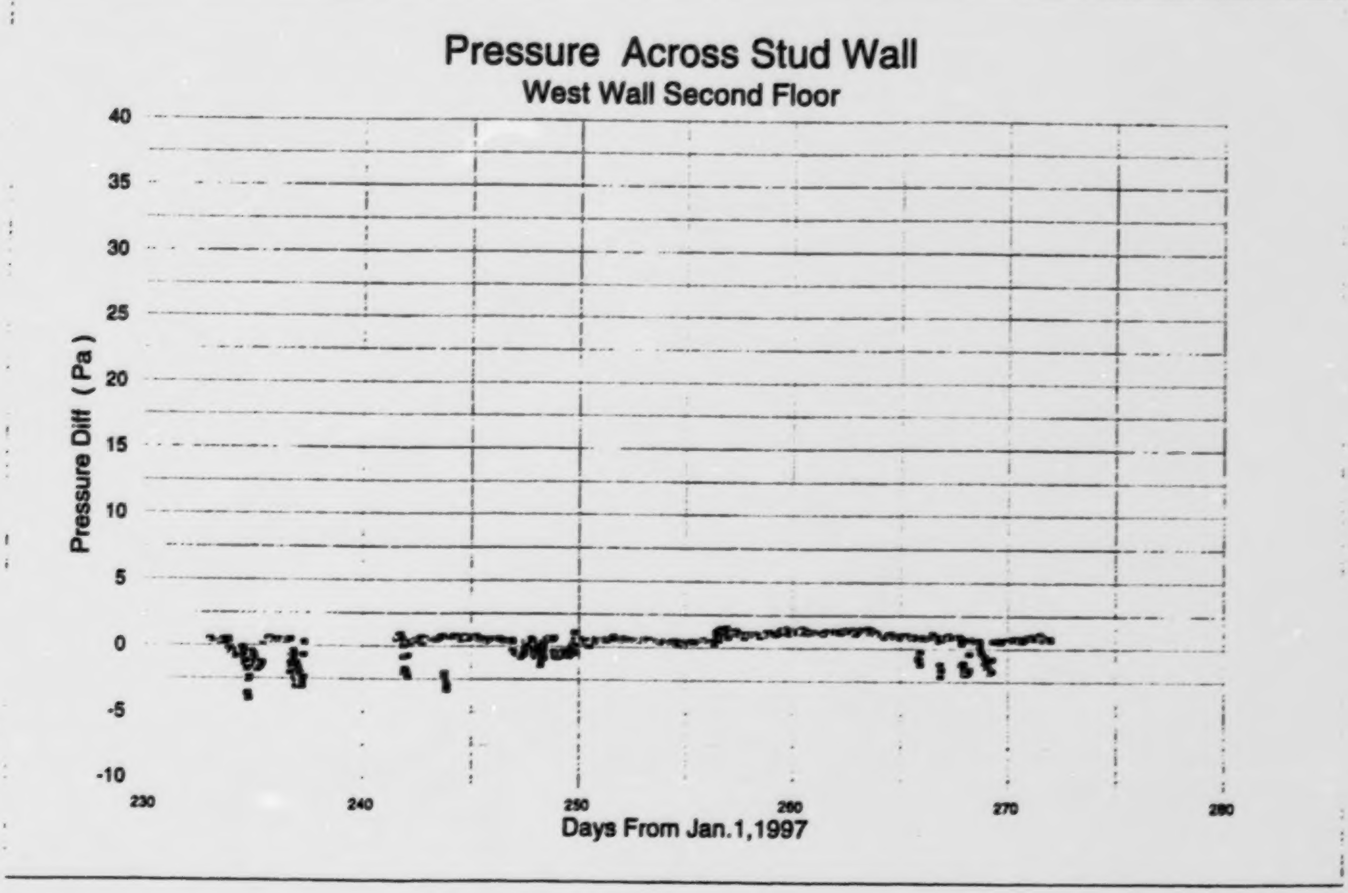

Figure 5. Pressure Across Stud Wall

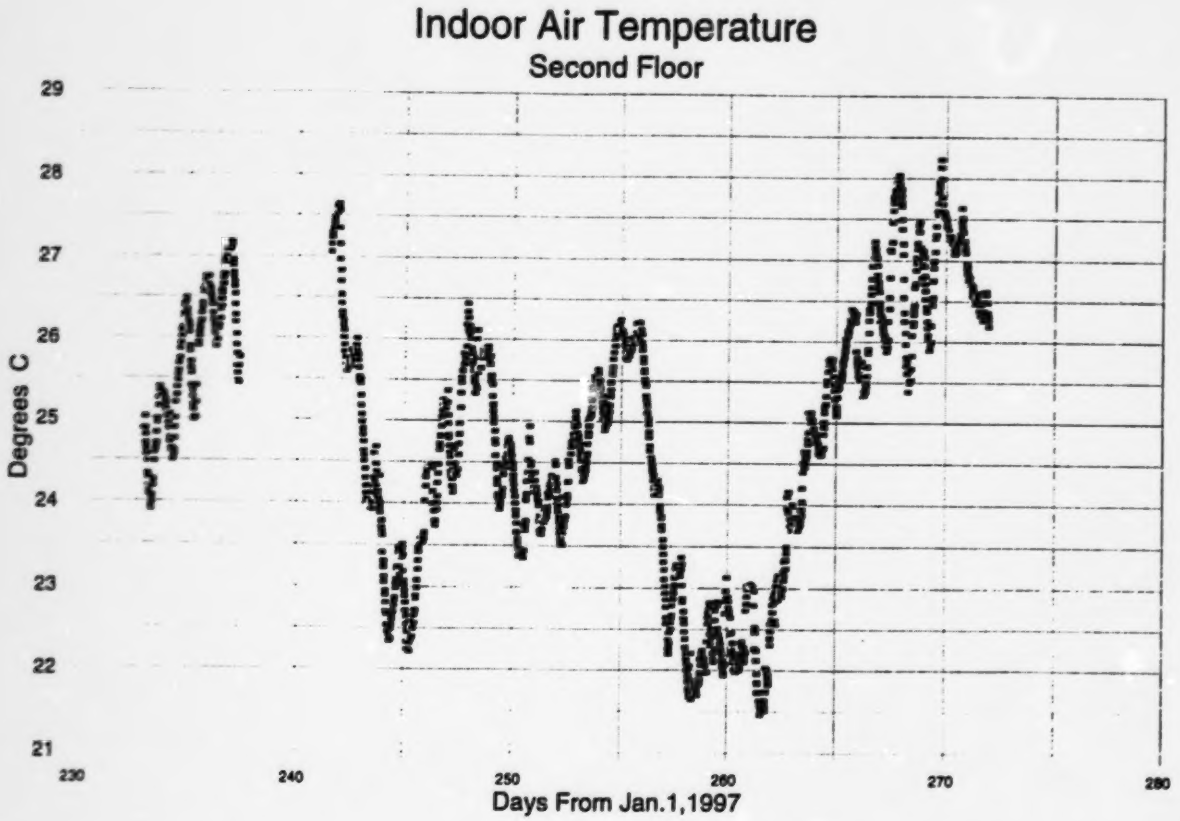

Figure 6. Indoor Air Temperature

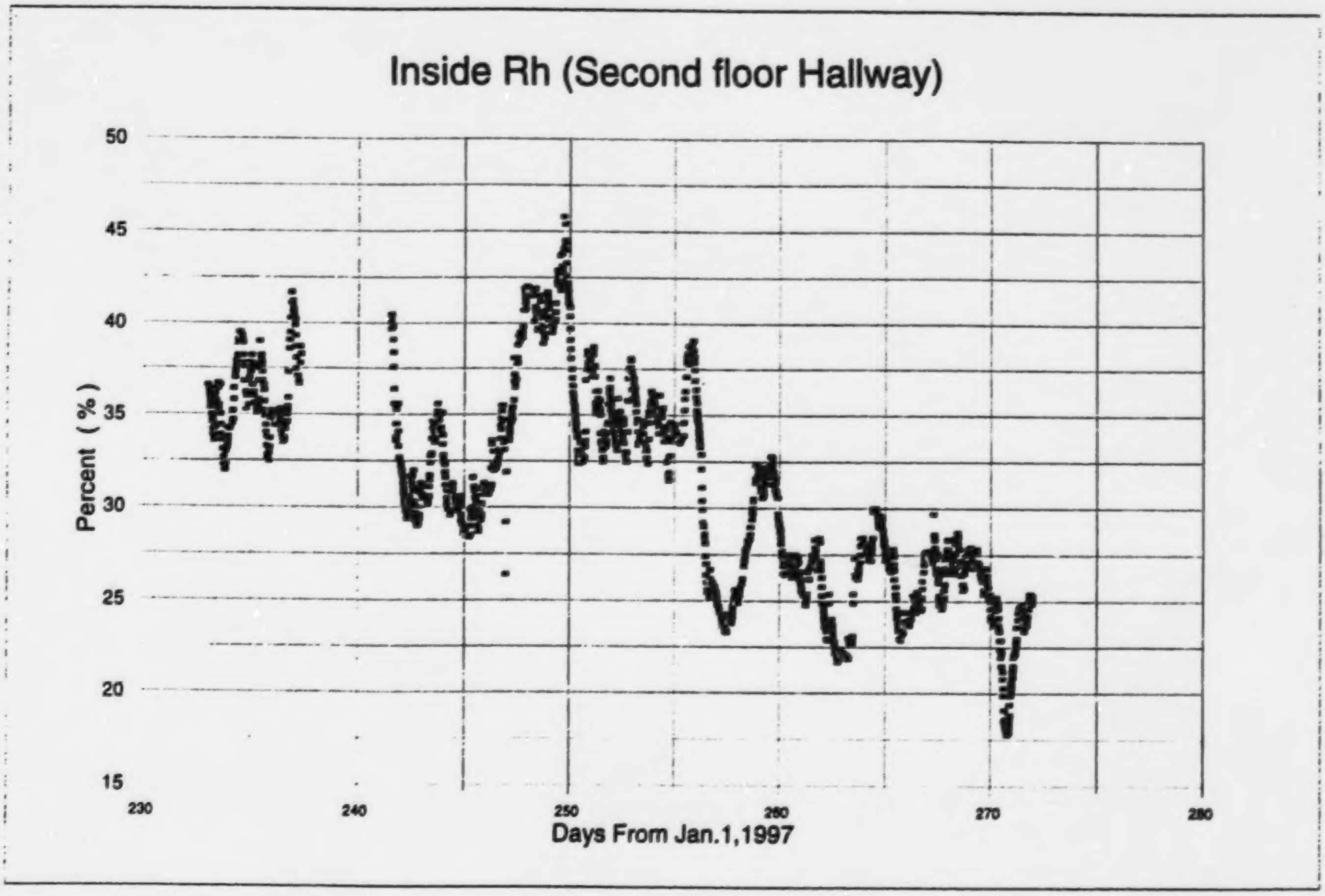

Figure 7. Inside Relative Humidity

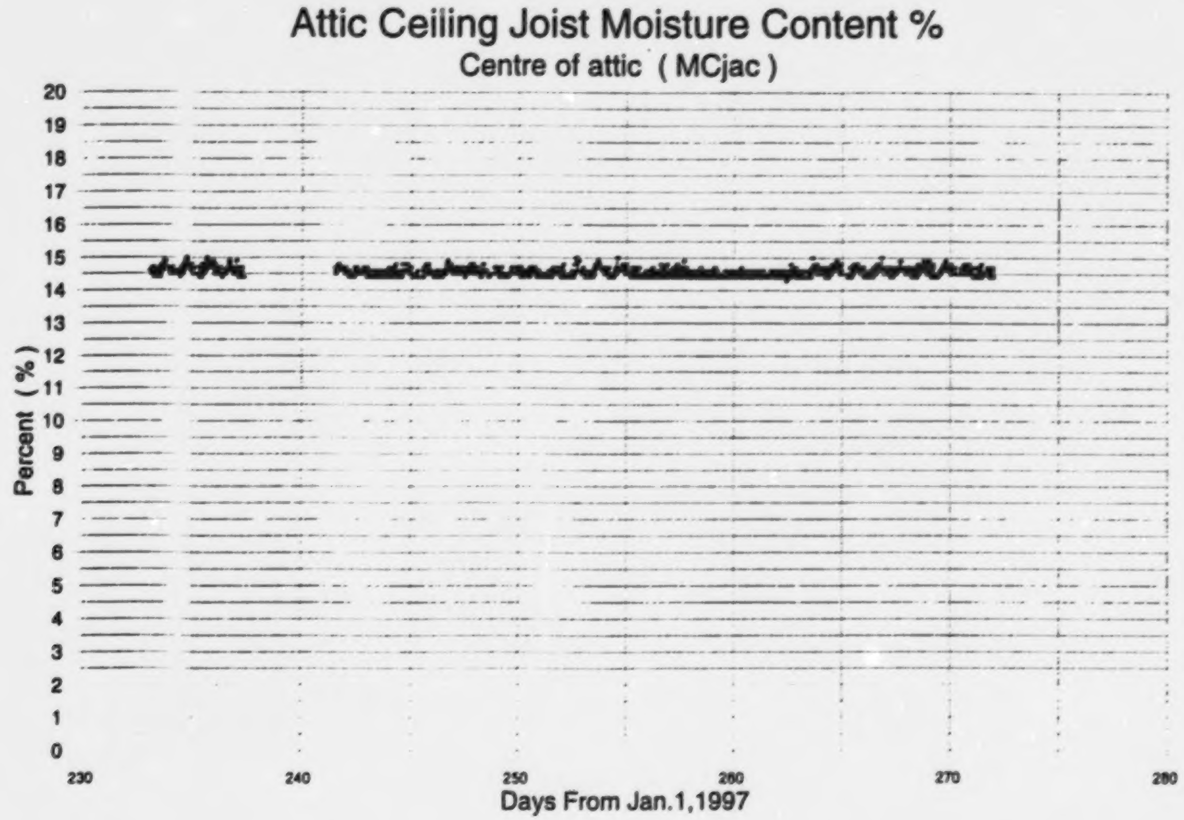

Figure 8. Attic Joist Moisture Content

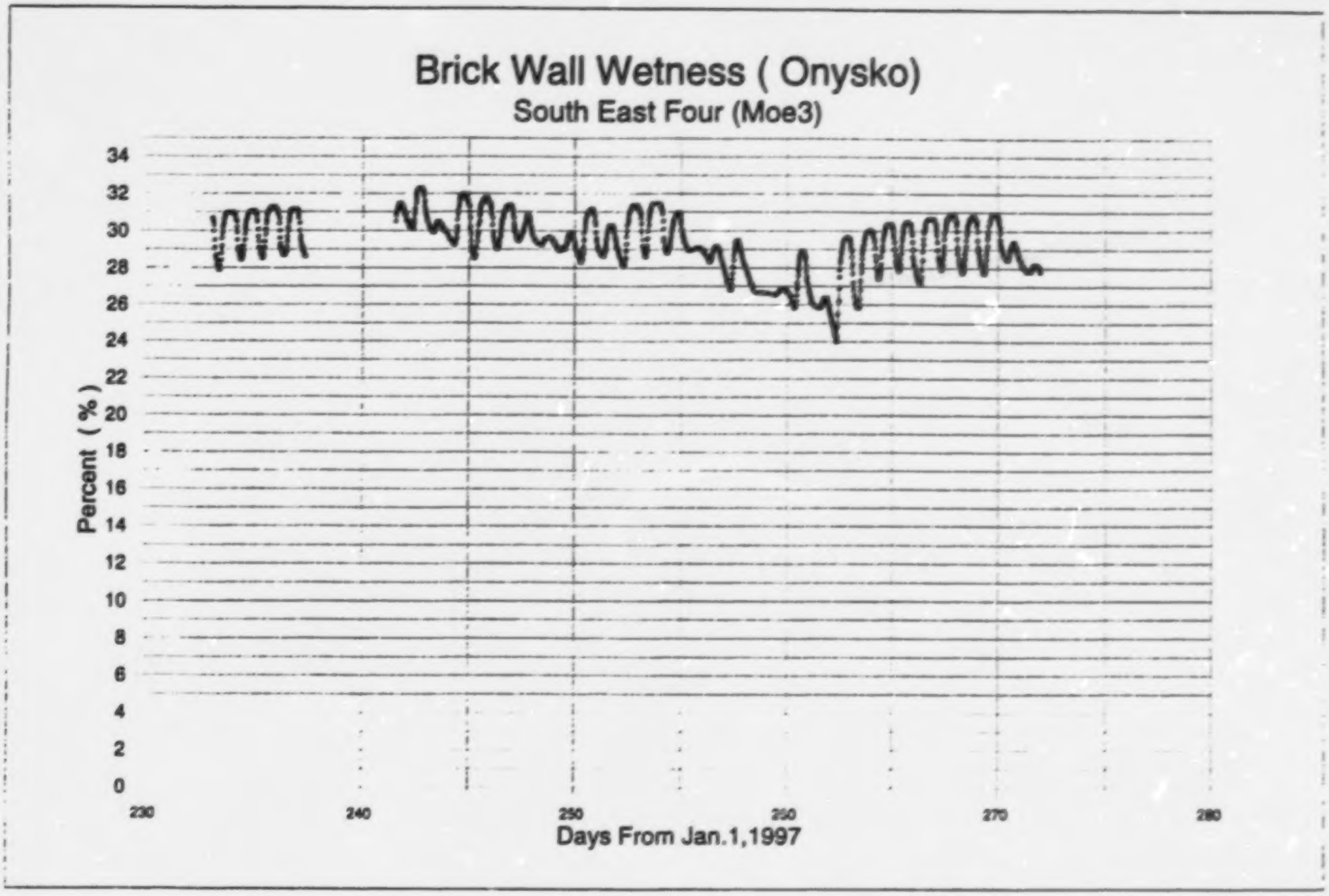

Figure 9. Brick Wall Wetness

APPENDIX A

Scan Intervals for the Various Sensors

Karcher Apartment Building Task Karch-06

Element Number	Monitored Parameter	CoPilot Codes	Scan Rate	Type of Sensor	Sensor Signal	Units	Channel Number
1	WIND SPEED ELEMENTS		5 secs			m/s	0
2	Wind Speed - average	Sw	5 secs			m/s	
3	Wind Speed - minimum	Swmin		DataOperator		m/s	
4	Wind Speed - maximum	Swmax		DataOPerator		m/s	
5	Wind Speed Frequency 0-2m/s	Fs02		Data Operator		%	
6	Wind Speed Frequency 2-4m/s	Fs24		Data Operator		%	
7	Wind Speed Frequency 4-6m/s	Fs46		Data Operator		%	
8	Wind Speed Frequency 6-8m/s	Fs68		Data Operator		%	
9	Wind Speed Frequency 8-10m/s	Fs810		Data Operator		%	
10	Wind Speed Frequency 10-12m/s	Fs1012		Data Operator		%	
11	Wind Speed Frequency 12-14m/s	Fs1214		Data Operator		%	
12	Wind Speed Frequency 14-16m/s	Fs1416		Data Operator		%	
13	Wind Speed Frequency 16-18m/s	Fs1618		Data Operator		%	
14	Wind Speed Frequency 18-20m/s	Fs1820		Data Operator		%	
15	Wind Speed Frequency 20-22m/s	Fs2022		Data Operator		%	
16	Wind Speed Frequency 22-24m/s	Fs2224		Data Operator		%	
17	Wind Speed Frequency >=24m/s	Fs24		Data Operator		%	
18	Wind Power density	Pwd		Data Operator		W/m	
19	WIND DIRECTION ELEMENTS		5secs	Scan Group			
20	Wind Direction	Dw			DC Voltage	Degree	1
21	Wind dir. freq. - N 337.5-22.5	Fdwn		DataOperator		%	
22	Wind dir. freq. - NE 22.5-67.5	Fdwne		DataOperator		%	
23	Wind dir. freq. - E 67.5-112.5	Fdwe		DataOperator		%	
24	Wind dir. freq. - SE 112.5-157.5	Fdwse		DataOperator		%	
25	Wind dir. freq. - S 157.5-202.5	Fdws		DataOperator		%	
26	Wind dir. freq. - SW 202.5-247.5	Fdwsw		DataOperator		%	
27	Wind dir. freq. - W 247.5-292.5	Fdww		DataOperator		%	
28	Wind dir. freq. - NW 292.5-337.5	Fdwnw		DataOperator		%	
29							
30							
31							
32							
33							
34							
35							
36							
37	ATMOSPHERIC ELEMENTS			Scan Group			
38	Outside temperature	Tout	60sec	Thermistor		xC	2
39	Outside Relative Humidity	RHout	60sec		DCVoltage	%	3
40							
41	Rainfall on Roof	RNroof	60sec	InternalCounter		mm	
42	Rainfall near NW corner	RNnw	60sec	InternalCounter		mm	
43	Rainfall near SE corner	RNse	60sec	InternalCounter		mm	
44							
45	ATMOSPHERIC ELEMENTS			Scan Group			
46	Horizontal Radiation voltage	V	5sec		DC Voltage	V	4
47	Horizontal Radiation	SOLhor	5sec	Pyranometer		W/m2	
48							
49							
50							
51							

52							
53							
54							
55	ATTIC ELEMENTS						
56	Attic temperature	Tattic	60sec	Thermocouple		xC	32
57	Attic RH	RHattic	60sec		DC Voltage	%	5
58							
59	Attic joist north: Pin resistance	Rajn	1200		Resistance	kohms	6
60	Attic joist north: Moisture content	MCajn	1200		DataOperator	%mc	
61	Attic joist centre: Pin resistance	Rajc	1200		Resistance	kohms	7
62	Attic joist centre: Moisture content	MCajc	1200		DataOperator	%mc	
63	Attic joist south: Pin resistance	Rajs	1200		Resistance	kohms	8
64	Attic joist south: Moisture content	MCajs	1200		DataOperator	%mc	
65							
66	Attic joist N wall NW: Onysko resistance	Rajnw	1200		Resistance	kohms	9
67	Attic joist N wall NW: Moisture content	MCajnw	1200		DataOperator	%mc	
68	Attic joist N wall NC: Onysko resistance	Rajnc	1200		Resistance	kohms	10
69	Attic joist N wall NC: Moisture content	MCajnc	1200		DataOperator	%mc	
70	Attic joist N wall NE: Onysko resistance	Rajne	1200		Resistance	kohms	11
71	Attic joist N wall NE: Moisture content	MCajne	1200		DataOperator	%mc	
72							
73	NW1 ELEMENTS						
74	NW1 heat flow meter: Voltage	HFMnw1	60sec		DC Voltage	mV	77
75	NW1 heat flow meter: Temperature	Thfnw1	60sec	Thermocouple		xC	33
76							
77	NW1 temp: Outside surface of stucco 6	T6nw1	300sec	Thermocouple		xC	34
78	NW1 temp: Inside surface of stucco 5	T5nw1	300sec	Thermocouple		xC	35
79	NW1 temp: Inside surface of brick 4	T4nw1	300sec	Thermocouple		xC	36
80	NW1 temp: Inside surface of insul 3	T3nw1	300sec	Thermocouple		xC	37
81	NW1 temp: Inside surface of drywall 2	T2nw1	300sec	Thermocouple		xC	38
82	NW1 temp: Suite in air 1	T1nw1	300sec	Thermocouple		xC	39
83	NW1 RH: Cavity	Rhcnw1	300sec		DC Voltage	%	78
84	NW1 Press diff: brick wall	PDbnw1	120sec		DC Voltage	Pa	79
85	NW1 Press diff: stud wall	PDsnw1	120sec		DC Voltage	Pa	80
86							
87	NW1 SRC sensor: Resistance	Rsnw1	1200		Resistance	kohms	82
88	NW1 ONYSKO sensor: Resistance	Ronw1	1200		Resistance	kohms	83
89	NW1 ONYSKO sensor: Moisture Content	Monw1	1200		DataOperator	%mc	
90	W2 ELEMENTS				Scan Group		
91	W2 lower heat flow meter 1: Voltage	HFM1w2	60sec		DC Voltage	mV	84
92	W2 upper heat flow meter 2: Voltage	HFM2w2	60sec		DC Voltage	mV	85
93	W2 heat flow meter: Temperature	Thfw2	60sec	Thermocouple		xC	40
94	W2 temp: Outside surface of stucco 6	T6w2	300sec	Thermocouple		xC	41
95	W2 temp: Inside surface of stucco 5	T5w2	300sec	Thermocouple		xC	42
96	W2 temp: Inside surface of brick 4	T4w2	300sec	Thermocouple		xC	43
97	W2 temp: Inside surface of insul 3	T3w2	300sec	Thermocouple		xC	44
98	W2 temp: Inside surface of drywall 2	T2w2	300sec	Thermocouple		xC	45
99	W2 temp: Suite in air 1	T1w2	300sec	Thermocouple		xC	46
100	W2 RH: Cavity	RHcw2	300sec		DC Voltage	%	86
101	W2 Press diff: brick wall	PDbw2	120sec		DC Voltage	Pa	87
102	W2 Press diff: stud wall	PDsw2	120sec		DC Voltage	Pa	88
103							
104	W2 SRC sensor: Resistance	Rsw2	1200		Resistance	kohms	90
105	W2 ONYSKO sensor: Resistance	Row2	1200		Resistance	kohms	91
106	W2 ONYSKO sensor: Moisture Content	Mow2	1200		DataOperator	%mc	

107	E3 ELEMENTS				Scan Group		
108	E3 lower heat flow meter 1: Voltage	HFM1e3	60sec		DC Voltage	mV	94
109	E3 upper heat flow meter 2: Voltage	HFM2e3	60sec		DC Voltage	mV	95
110	E3 heat flow meter: Temperature	Thfe3	60sec	Thermocouple		xC	47
111	E3 temp: Outside surface of stucco 6	T6e3	300sec	Thermocouple		xC	48
112	E3 temp: Inside surface of stucco 5	T5e3	300sec	Thermocouple		xC	49
113	E3 temp: Inside surface of brick 4	T4e3	300sec	Thermocouple		xC	50
114	E3 temp: Inside surface of insul 3	T3e3	300sec	Thermocouple		xC	51
115	E3 temp: Inside surface of drywall 2	T2e3	300sec	Thermocouple		xC	52
116	E3 temp: Suite in air 1	T1e3	300sec	Thermocouple		xC	53
117	E3 RH: Cavity	RHce3	300sec		DC Voltage	%	96
118	E3 Press diff: brick wall	PDbe3	120sec		DC Voltage	Pa	97
119	E3 Press diff: stud wall	PDse3	120sec		DC Voltage	Pa	98
120							
121	E3 SRC sensor: Resistance	Rse3	1200		Resistance	kohms	100
122	E3 ONYSKO sensor: Resistance	Roe3	1200		Resistance	kohms	101
123	E3 ONYSKO sensor: Moisture Content	Moe3	1200		DataOperator	%mc	
124	SE4 ELEMENTS				Scan Group		
125	SE4 lower heat flow meter 1: Voltage	HF1se4	60sec		DC Voltage	mV	104
126	SE4 upper heat flow meter 2: Voltage	HF2se4	60sec		DC Voltage	mV	105
127	SE4 heat flow meter: Temperature	Thfse4	60sec	Thermocouple		xC	54
128	SE4 temp: Outside surface of stucco 6	T6se4	300sec	Thermocouple		xC	55
129	SE4 temp: Inside surface of stucco 5	T5se4	300sec	Thermocouple		xC	56
130	SE4 temp: Inside surface of brick 4	T4se4	300sec	Thermocouple		xC	57
131	SE4 temp: Inside surface of insul 3	T3se4	300sec	Thermocouple		xC	58
132	SE4 temp: Inside surface of drywall 2	T2se4	300sec	Thermocouple		xC	59
133	SE4 temp: Suite in air 1	T1se4	300sec	Thermocouple		xC	60
134	SE4 RH: Cavity	RHcse4	300sec		DC Voltage	%	106
135	SE4 Press diff: brick wall	PDbse4	120sec		DC Voltage	Pa	107
136	SE4 Press diff: stud wall	PDsse4	120sec		DC Voltage	Pa	108
137							
138	SE4 SRC sensor: Resistance	Rsse4	1200		Resistance	kohms	110
139	SE4 ONYSKO sensor: Resistance	Rose4	1200		Resistance	kohms	111
140	SE4 ONYSKO sensor: Moisture Content	Mose4	1200		DataOperator	%mc	
141	N4 ELEMENTS				Scan Group		
142	N4 lower heat flow meter 1: Voltage	HF1n4	60sec		DC Voltage	mV	114
143	N4 upper heat flow meter 2: Voltage	HF2n4	60sec		DC Voltage	mV	115
144	N4 heat flow meter: Temperature	Thfn4	60sec	Thermocouple		xC	61
145	N4 temp: Outside surface of stucco 6	T6n4	300sec	Thermocouple		xC	62
146	N4 temp: Inside surface of stucco 5	T5n4	300sec	Thermocouple		xC	63
147	N4 temp: Inside surface of brick 4	T4n4	300sec	Thermocouple		xC	64
148	N4 temp: Inside surface of insul 3	T3n4	300sec	Thermocouple		xC	65
149	N4 temp: Inside surface of drywall 2	T2n4	300sec	Thermocouple		xC	66
150	N4 temp: Suite in air 1	T1n4	300sec	Thermocouple		xC	67
151	N4 RH: Cavity	RHcn4	300sec		DC Voltage	%	116
152	N4 Press diff: brick wall	PDbn4	120sec		DC Voltage	Pa	117
153	N4 Press diff: stud wall	PDsn4	120sec		DC Voltage	Pa	118
154							
155	N4 SRC sensor: Resistance	Rsn4	1200		Resistance	kohms	120
156	N4 ONYSKO sensor: Resistance	Ron4	1200		Resistance	kohms	121
157	N4 ONYSKO sensor: Moisture Content	Mon4	1200		DataOperator	%mc	
158	NW4 ELEMENTS				Scan Group		
159	NW4 lower heat flow meter 1: Voltage	HF1nw4	60sec		DC Voltage	mV	124
160	NW4 upper heat flow meter 2: Voltage	HF2nw4	60sec		DC Voltage	mV	125
161	NW4 level 4 heat flow meter: Temperature	Thfnw4	60sec	Thermocouple		xC	68

162	NW4 temp: Outside surface of stucco 6	T6nw4	300sec	Thermocouple		xC	69
163	NW4 temp: Inside surface of stucco 5	T5nw4	300sec	Thermocouple		xC	70
164	NW4 temp: Inside surface of brick 4	T4nw4	300sec	Thermocouple		xC	71
165	NW4 temp: Inside surface of insul 3	T3nw4	300sec	Thermocouple		xC	72
166	NW4 temp: Inside surface of drywall 2	T2nw4	300sec	Thermocouple		xC	73
167	NW4 temp: Suite in air 1	T1nw4	300sec	Thermocouple		xC	74
168	NW4 RH: Cavity	RHcnw4	300sec		DC Voltage	%	126
169	NW4 Press diff: brick wall	PDbnw4	120sec		DC Voltage	Pa	127
170	NW4 Press diff: stud wall	PDsnw4	120sec		DC Voltage	Pa	128
171							
172	NW4 SRC sensor: Resistance	Rsnw4	1200		Resistance	kohms	130
173	NW4 ONYSKO sensor: Resistance	Ronw4	1200		Resistance	kohms	131
174	NW4 ONYSKO sensor: Moisture Content	Monw4	1200		DataOperator	%mc	
175	EXHAUST AIR ELEMENTS						
176	Exhaust air level 2: RH	RHexh	60sec		DC Voltage	%	134
177	Exhaust air level 2: Temperature	Texh	60sec	Thermocouple		xC	75
178							
179							
180							
181							
182							
183							
184							
185							
186							
187							
188	MONITORING ADMINISTRATION						
189	Thermocouple junction temperature	Tjcn		Thermistor		xC	Internal
190	Zero Voltage check	Vzero	300sec		DC Voltage	uV	136
191	Voltage Constant	Vconst	300sec		DC Voltage	V	137
192	Time in a save period	TMsvpd	seconds	DataOperator			
193							
194	SI 231 A/D converter	si231	L9024	EMCS Equip			
195	SI 240 Counter/Timer	si240	L9024	EMCS Equip			
196							
197	Save monitored parametrs	SAmon	30min	Saves		saves	
198						saves	
199	SCAN ELEMENTS					saves	
200	Scan elements which need initialisation	SCinit	nce on start u	PrioriScan		saves	
201	Scan wind speed parameters-1	SCws1	5sec	PrioriScan		saves	
202	Scan wind speed parameters-2	SCws2	5sec	PrioriScan		saves	
203	Scan wind direction parameters	SCwd	5sec	PrioriScan			
204	Scan outside, attic, exhaust air	SCoae	60sec	Scan List			
205	Scan heat flow meters-NW1, W2, E3	SChfm1	60sec	Scan List		scans	
206	Scan heat flow meters-SE4, N4, NW4	SChfm2	60sec	Scan List		scans	
207	Scan press. diff. - NW1, W2, E3	SCpd1	120sec	Scan List		scans	
208	Scan press. diff. - SE4, N4, NW4	SCpd2	120sec	Scan List		scans	
209	Scan NW1 inside conditions	SCnw1	300	Scan List		scans	
210	Scan W2 inside conditions	SCw2	300	Scan List		scans	
211	Scan E3 inside conditions	SCe3	300	Scan List		scans	
212	Scan SE4 inside conditions	SCse4	300	Scan List		scans	
213	Scan N4 inside conditions	SCn4	300	Scan List		scans	
214	Scan NW4 inside conditions	SCnw4	300	Scan List		scans	
215	Scan attic joist sensors	SCaj	1200	Scan List		scans	
216	Scan attic joist N wall sensors	SCajnw	1200	Scan List		scans	

217	SCAN MOISTURE SENSORS				scans
218	Scan moisture sensors-NW1, W2	SCm1	1200	Scan List	scans
219	Scan moisture sensors-E3, SE4	SCm2	1200	Scan List	scans
220	Scan moisture sensors-N4, NW4	SCm3	1200	Scan List	scans
221	Scan Pyranometer	SCpyr		PrioriScan	scans
222					
223					scans
224					scans
225					scans
226					scans
227					
228					
229					
230					
231					
232					
233					
234	EQUATIONS				
235	Eqn: RH threshold - 0-100%	eRHth		Equation	
236	Eqn: Wind speed threshold - 0-50 m/m	eSWth		Equation	
237	Eqn: Wind Power density	ePwd		Equation	
238	Eqn: Direction threshold - N	eDTn		Equation	
239	Eqn: Direction threshold - NE	eDTne		Equation	
240	Eqn: Direction threshold - E	eDTe		Equation	
241	Eqn: Direction threshold - SE	eDTse		Equation	%
242	Eqn: Direction threshold - S	eDTs		Equation	m/s
243	Eqn: Direction threshold - SW	eDTsw		Equation	W/m
244	Eqn: Direction threshold - W	eDTw		Equation	%
245	Eqn: Direction threshold - NW	eDTnw		Equation	%
246	Eqn: Attic joist north moisture content	eMCajn		Equation	%
247	Eqn: Attic joist centre moisture content	eMCajc		Equation	%
248	Eqn: Attic joist south moisture content	eMCajs		Equation	%
249	Eqn: Attic joist N wall NW moisture content	eMCjnw		Equation	%
250	Eqn: Attic joist N wall NC moisture content	eMCjnc		Equation	%
251	Eqn: Attic joist N wall NE moisture content	eMCjne		Equation	%
252	Eqn: NW1 ONYSKO sensor: Moisture conten	eMonw1		Equation	%
253	Eqn: W2 ONYSKO sensor: Moisture content	eMow2		Equation	%
254	Eqn: E3 ONYSKO sensor: Moisture content	eMoe3		Equation	%
255	Eqn: SE4 ONYSKO sensor: Moisture content	eMose4		Equation	%
256	Eqn: N4 ONYSKO sensor: Moisture content	eMon4		Equation	%
257	Eqn: NW4 ONYSKO sensor: Moisture conten	eMonw4		Equation	%
258	Horizontal Solar Radiation	eSolhr		Equation	%
259	Const: 1	c1		Equation	%
260	Const: Wind speed thresh. for direction	cWSdth		Equation	%
					%
					%
					W/m2
					1
	G:\bpdocs\larry\karcho6.wb2				m/s

APPENDIX B

Data Logger Monitoring Sensor List

APPENDIX B

Data Logger Monitoring Sensor List

Sensor	Make	Model	Output	# Installed
Thermocouple	Thermo Electric	TYPE-T 24 Gauge	mV	45
Thermistor	YSC	4405 (3000 SL)	OHMS	1
Wood w/c	Delmhorst	Pins	OHMS	3 pairs
Wetness	ONYSKO	(WO)	OHMS	9
Wetness	SRC	(WS)	OHMS	6
Pressure Transducer	Dwyer	607-3 (0-250 Pa)	4-20mA	12
Heat Flow Transducer	Made by SRC	Used Calibrated Foam Insulation (Plastifab EPS)	mV	11
Rh	VAISALA	Humitter 50A	0-5VDC	7
Rh	VAISALA	HMP35CF	0-1VDC	1
Rh	General Eastern	RH-2 Ductmount	0-20mA	1
Rain Guage	Texas Electronics	TE525M	0.1mm/count	3
Wind Speed/ Dir	RM Young	05103	0-5VDC	1
Solar Radiation	LI-COR	LI-2005B	VDC	1

PA Apartment Sensor List

Sensor	NW4	NW1	N4	W2	E3	SE4	Attic	Weather Station	Other
Thermocouple	7	7	7	7	7	7	1	1	
Thermistor								1	
Wood w/c							3		
Moisture sensor SRC (WS)	1	1	1	1	1	1			
Moisture sensor Onysko (WO)	1	1	1	1	1	1	3		
Pressure Transducer (PT)	2	2	2	2	2	2			
HFT	2	1	2	2	2	2			
Rh	1	1	1	1	1	1	1	1	
Rain								1	2
Exhaust air Rh									1
Exhaust air Temp.									1
Wind speed								1	
Wind dir.								1	
O volts									1
SubTotal	14	13	14	14	14	14	8	5	5

Total Channels = 101

G:\BSD\PASENSOR.WPD

INTERIM REPORT #3

The Renovation of an Apartment Building with Solid Masonry Walls

for

High-Rise Innovation Centre
Canada Mortgage and Housing Corporation

by

Building Performance
Saskatchewan Research Council

Small Industry Services

February, 1998

Introduction

This report is the third interim report on the renovation of an Apartment Building with Solid Masonry Walls.

In this report the following items are discussed:

1. Sensor calibrations for the data logging system.
2. Neutral pressure level measurements taken at the site.
3. Furnace room odour problem
4. Energy readings for the facility.

1. Sensor calibrations for the data logging system.

There are 12 types of sensors used on the data logging system:

1. Thermocouples
2. Heat flux transducers
3. Pressure transducers
4. Wood moisture pins
5. Onysko moisture sensors
6. Wind speed
7. Wind direction
8. Relative humidity sensors
9. Rain gauge
10. Solar radiation
11. Thermistor
12. SRC Wetness sensor

All of the sensors used on the building were either new or had been recalibrated prior to installation. At the time of installation in late July of 1997, the sensors were also checked to see that reasonable results were being achieved. Sensor drift, however, is always a potential problem with transducers. In addition to sensor drift, there is also the potential problem of data logger voltage drift. To monitor this problem, a zero volt channel and another channel with a voltage of 2.5 volts are continually monitored and stored every half hour with the other data logger readings. The following checks were performed on November 19, 1997 on a number of the sensors.

1. Thermocouples

A distilled water and ice solution was brought to the apartment building and the following thermocouples sensor were checked to see that accurate values were being recorded:

Thermocouple Location	Temperature when immersed in ice bath of distilled water and ice (°C)
NW1 Suite Air	-0.04
E3 Suite Air	-0.06
NW 4 Suite Air	-0.02

As can be seen from the above table, the readings from the three thermocouples were all within 0.06 °C of the distilled water temperature of 0 °C.

2. Heat Flux Transducers

The heat flux transducers consist of 25.4 mm thick pieces of expanded polystyrene insulation with a width of 300 mm and a height of 300 mm. The thermal resistance value of each piece of insulation was measured by the supplier, Plastifab of Calgary. A total of 8 thermocouples were placed in series on each of the polystyrene pieces. The insulation has a thermal resistance value of approximately 0.68 m^2 °C/ W. The thermocouples have an output of about 40.7 microvolts per C, and there are a total of 8 sets of thermocouples, resulting in a voltage output of about 326 microvolts per C. Thus the transducers have an output of 326 * 0.68 = 221 microvolts/(watt/m2).

Using data from November 18 for the SouthEast 4 transducer, the temperature difference across the wall insulation amounted to 22.3 °C, and the corresponding voltage output from the transducer was 1071 uV. The calculated heat flux was 1071/221 = 4.84 W/m2. Dividing the temperature difference for the wall by the heat flux results in the RSI value of 4.6 m^2°C/ W.

For comparison, the nominal batt insulation value is RSI 3.5, and the heat flux transducer thermal resistance is RSI 0.68, for a total wall insulation value of RSI 4.2. This is a difference of about 10% from the measured value of RSI 4.6.

This check was performed to assure ourselves that reasonable results were being achieved. A more detailed analysis of the exact output of each transducer will later be developed, and a more accurate calculation will be possible.

An interesting phenomenon was observed in that some of the heat flux transducers were providing values that were consistently different from other transducers.

For instance, the following values were found for the time of 6 am on November 18.

Heat Flux Transducer Location	Millivolt output from heat flux transducer (mV)	Room Temp C	Inside of Brick Temp C	Temp Difference C	HFT Output/ Temp diff (uV/C)
NW1	0.918	19.3	-2.07	17	53
W2 Lower	0.957	21.1	1.31	22	43
W2 Upper	1.01	21.1	1.31	22	45
E3 Lower	0.988	20.8	-1.3	20	51
E3 Upper	1.135	20.8	-1.3	20	58
SE4 Lower	1.191	21.4	-1.0	20	58
SE4 Upper	1.081	21.4	-1.0	20	53
N4 Lower	1.111	18.6	1.3	20	56
N4 Upper	0.816	18.6	1.3	20	41
NW4 Lower	0.726	19.4	-2.3	17	42
NW4 Upper	1.053	19.4	-2.3	17	62
Averages	0.999	20.2	-0.55	20	51

Outdoor air temperature = -8.3 C

As the heat flux transducer output values from the 11 transducers showed a considerable difference, even when adjusted for varying room temperatures, it was decided to investigate each of the rooms to see if anything unusual was happening. As can be seen from the above table, the heat flux values from sensors in W2 (Upper and Lower), N4 Upper, and NW4 Lower were all considerably lower than those found from the other sensors.

Photographs of the walls on which the heat flux transducers were incorporated are shown in figures 1 and 2.

As can be seen from the photographs, a number of unusual conditions were discovered. In room W2, a television set is located in the room. The heat from the TV set may be giving a false temperature reading to the room temperature sensor. In room E3, boxes were stacked against the lower part of the outside wall. As expected, the lower transducer was showing a lower heat transfer rate. The sensors are located at 0.915 metres (lower sensor) and 1.680 metres (upper sensor) above the floor. At sensor N4 (upper), a closet had been built adjacent to the sensor, and a sleeping bag was pushed against the wall, thus reducing the heat transfer. At sensor NW4 Lower there was a table pushed against the wall.

These field conditions help to explain the anomalous heat flux transducer readings, and also point to the challenging conditions under which field data must be collected.

Based on the above conditions, it is recommended that the N4 Sensor values be ignored because of the abutting wall and closet. The occupants of the other suites will be asked to move the material away from the wall for the duration of the testing.

3. Pressure Transducers

There are a total of 12 pressure transducers in the building. These transducers measure the pressure difference across the brick wall and across the stud wall at the same locations where the heat flux transducers are located. The pressure transducers are Dwyer Model 607-3 units with a range from 0 to 250 pascals. The output of the transducers is a 4 to 20 milliamp signal which is converted at the computer to a voltage and then to a pascal reading. The transducers were checked for zero readings, and also for span, prior to installation in late July, 1997, and were found to be within specification limits.

On November 19, 1997, each of the pressure transducers was checked for zero and span again.

A digital manometer (Minneapolis Blower Door Model Number A0753) was used to check the calibration of the pressure transducers. In turn, the calibration of the digital manometer had been checked in November 1997 using a BETZ micro manometer which uses a very accurate scale and distilled water.

The pressure transducers did exhibit a small amount of zero drift. A listing of the zero drift measured on the sensors is shown in the following table.

Pressure Transducer	Zero Drift Measured (Pa)
NW1 Brick	-0.4
NW1 Stud	1.0
W2 Brick	-1.0
W2 Stud	1.1
E3 Brick	0.3
E3 Stud	0.4
SE4 Brick	0.2
SE4 Stud	-0.6
NW4 Brick	0.9
NW4 Stud	0.08
N4 Brick	0.65
N4 Stud	0.6

As can be seen, the zero drift over the 3.5 month period was relatively small, with a maximum of 1.0 Pa being recorded.

After recording the zero drift, the zero was reset on each of the transducers.
The span on each of the transducers was also checked, and all of the transducers were within 1% of full scale accuracy.

4. Wood moisture pins

The accuracy of the wood moisture pin readings were checked against a self-calibrating Delmhorst wood moisture meter at the time of installation. Jumper leads were used to connect the Delmhorst meter to wires leading to the moisture pins in the building. As the voltmeter on the data logger was found to be reading accurately, the moisture pin readings are considered accurate as well.

5. Onysko moisture pins

A technique similar to that used with the wood moisture pins was used with the Onysko moisture pins.

The following table lists the moisture content readings for the Onysko sensors located in the brick walls of the building.

Onysko Sensor Location	Moisture Content Reading of the Sensor (%)	Temperature at the inside of the brick C
NW1	5.7	-2.1
W2	7.8	1.3
E3	9.7	-1.3
SE4	27.9*	2.4
N4	11.6	1.3
NW4	13.1	-2.3

*This sensor was not reading at that time. The value shown is the value for November 27 at 6 am, when the temperature in the cavity at the inside of the brick was 2.4 C.

All of the sensors were indicating dry conditions (less than 19%, the standard for kiln dried lumber), with the exception of the SE4 location. This is the location where the water penetration test was conducted in August 1996.

6. Wind speed

The anemometer used was calibrated prior to installation. It was found, however, that the pressure difference readings across the brick wall were considerably higher than those expected given the measured wind speeds on site. A plot comparing the wind speed measured on the tower on the top of the apartment building with the airport measured value is presented in figure 3. As can be seen, the airport measured value is considerably higher than the site measured value. It is believed that the presence of adjacent tall buildings contributes to the attenuation of the wind speeds. It has been observed that during high wind conditions, the direction indicator on the mast turns frequently, indicating a large amount of turbulence in the wind.

7.Wind Direction

A compass was used to locate the wind sensor. Qualitative checks have been used to verify that the direction indication is correct.

8. Relative humidity sensors

There are 6 RH sensors located in the walls of the building. These sensors were built into the walls, and are not accessible for testing. They are located just inside of the inner layer of brick in the cavity between the brick and the stud wall. The RH values measured in the 6 locations were as follows on November 18, 1997 at 6 am.

RH Sensor Location	Relative Humidity (%)	Temperature C
NW1	53.5	-2.1
W2	52.0	1.3
E3	62.4	-1.3
SE4	60.6	-1.0
N4	44.2	1.3
NW4	72.5	-2.3

The RH values range between 44.2% and 72.5%. It is known that the SE4 location would tend to be among the higher values, as this is the wall where a moisture penetration test was conducted in August, 1996. High RH values are also found at locations E3 and NW4. It is possible that some exfiltration of moist air may occur at these locations.

9. Rain Gauge

The sensor was calibrated at the factory.

10. Solar Radiation.

This sensor was originally calibrated, and according to the specialist technician who installed it, the calibration does not vary over time.

11. Thermistor for Outdoor Temperature

The thermistor is located in a weather shield on the roof. A comparison of the data logger output and the Environment Canada reading at the airport is shown in figure 4. As can be seen, the thermistor registers slightly higher readings for most of th time, likely due to the urban heat island phenomenon.

12. SRC Wetness Sensors

The SRC wetness sensor measures the DC electrical resistance across a filter paper. If the sensor is fully wet, the resistance falls to zero. If the sensor is totally dry, the resistance of the sensor is between 176 and 178 kilohms (176 to 178 kilohm resistors are placed in parallel with the filter paper.) The measured values for the sensors, which are placed at the some location as the Onysko sensors, are presented in the following table.

Wetness Sensor Location	Resistance (kilohms)	Temperature C
NW1	177	-2.1
W2	178	1.3
E3	176	-1.3
SE4	153	-1.0
N4	177	1.3
NW4	177	-2.3

The SE4 sensor is showing a presence of wetness, as its resistance is 153 kohms. All of the other sensors are dry.

Neutral Pressure Level Measurements

The neutral pressure level for the building was measured using the pressure difference readings from the data logger at a time when the wind speed was very low. By checking the data logger output, a time with a low wind speed was found. At 9:30 am on November 27, the average wind speed for the hour was 0.29 m/s (1.0 km/h). The pressure differences across the walls of the building are presented in figure 5 for the 6 pressure transducer locations. Because the pressure differences are relatively small (less than 14 pascals), these readings were taken after the pressure transducers were re-calibrated on November 19.

As can be seen from the graph, the entire building was experiencing a negative pressure relative to outdoors.

The reason for negative pressure is the imbalance on the supply and exhaust fans for the building.

According to the Air Balancing Contractor's Report (May, 1997), the supply flow for the building is 775 L/s, and the exhaust flow is 1159 L/s. This imbalance in flow causes the strong negative pressure in the building. The contractor has been asked to have the flows brought to balance. (A balanced flow of 987 L/s was specified.)

Referring to figure 5, the neutral pressure line normally should pass through the zero pressure value at roughly the mid-height of the building.(approximately 6 metres.) As can be seen from the graph, all the pressure taps in the building are showing a positive pressure difference relative to outdoors because of the strong excess of exhaust flow compared to the supply flow.

The best least-square curve fit for the line shown in figure 5 has a slope of -1.1 pascals/metre. The theoretical slope based on the indoor and outdoor temperatures and the local atmospheric pressure was calculated to be -1.3 pascals/metre. One reason that the measured slope does not agree exactly with the theoretical slope is that the exhaust and supply flows at each floor are not uniform from floor to floor. Other factors such as the small pressure differences across the doors within the building, and different room temperatures can cause the slope to vary from the theoretical.

Other information can be gained from the neutral pressure level measurements.

The pressure drops across the brick wall and the stud wall can be compared. The following table presents the measured data for the brick wall pressure difference as a percentage of the pressure difference across the entire wall.

PressureTransducer Location	Total Pressure Difference (Pa)	Brick Wall Pressure Difference as Fraction of Total Wall Pressure Difference
NW1	13.7	0.77
W2	10.3	0.88
E3	4.9	0.76
SE4	1.6	0.75
N4	1.7	0.76
NW4	1.3	0.92

As can be seen from the table, the brick wall, which has cement parging on the inside, provides a very large fraction of the overall air tightness of the total wall. The polyethylene vapour barrier and the gypsum board on the inner wall provide only a relatively small part of the overall wall air tightness.

It can also be seen from the above table that the pressure differences across the walls agree fairly well in the case of SE4, N4 and NW4, all of which are at the same height. The difference in the readings between the three sensors is only 0.4 pascals.

A whole building pressure test was performed on the building on April 7, 1997. At the time of the test, the pressure differences across the brick wall and across the stud wall were also measured. These results are presented in the following table, along with the results from the testing done in November, 1997.

Press Transducer Location	**Whole Building Pressure Test Result April 7, 1997** Brick Wall Pressure Difference as Fraction of Total Wall Pressure Difference	**Neutral Pressure Level Test Results November 28, 1997** Brick Wall Pressure Difference as Fraction of Total Wall Pressure Difference
NW1	0.77	0.77
W2	Plugged	0.88
E3	0.72	0.76
SE4	Plugged	0.75
N4	0.70	0.76
NW4	Plugged	0.92

The neutral pressure test results are quite consistent with the pressure difference measurements found during the whole building test conducted in April 1977. [In the April 1977 tests, three of the exterior wall pressure taps had been plugged by the stucco applicators. Some external cleaning was required to dislodge the material plugging the pressure taps.]

One of the reasons that the results do not exactly agree between the two sets of tests is because the two sets of tests were measured at different pressure difference levels, and the air flow through the walls is not linear with pressure difference. The whole building pressure test had an exponent (n) value in the flow versu pressure difference equation equal to 0.73

3. Furnace Room Odour Problem

A slight odour is noticeable in the boiler room related to combustion gases. The authors have a hypothesis that the odour is related to back drafting of the chimney/venting system caused by three factors. A sketch of the boiler room is shown in figure 6.

The three factors are as follows:

1. General negative pressure in the building relative to outdoors causes the chimney to draw poorly. This negative pressure is caused by the imbalance of exhaust flow over supply flow for the make-up ventilation air for the building.
2. The combustion air supply duct for the building may be undersized.
3. The supply air fan located in the boiler room draws air in through the coarse filter on the upstream side of the fan, as shown in figure 6.

The solution to the problem can likely be solved by the following.

1. Rebalance the supply and exhaust flows in the building.
2. Seal the ductwork on the upstream side of the supply air fan in the boiler room, along with the area where the side of the filter is located upstream of the fan. A measurable amount of air is drawn from the room by the filter opening.
3. If the above two measures do not solve the problem, add additional combustion air supply.

4. Energy Readings

Electrical Energy Use

Each of the suites in the apartment building has a utility supplied electrical meter. The common area electrical usage for the building is also metered with a utility-supplied meter. These meters are being read every two weeks by a subcontractor. A bar graph of the daily average electrical energy consumption for the suites is presented in figure 7. Each of the suites has a refrigerator and an electric stove, but no dishwasher. A coin operated clothes washer and electric dryer are present on each floor.

As can be seen from figure 7, the electricity consumption per suite ranged from a low of 0.3 kWh/day to a high of 12.4 kWh/day. The median value was 5.3 kWh/day, and the average was 5.6 kWh/day. The suite with the lowest electricity consumption, suite 302, is used as a common games room, and has no electric stove or refrigerator. Electric lighting is the only use in the room 302.

The common area electricity consumption includes the electricity for heating system pumps, fans, hallway lighting, exterior block heaters, clothes washers and dryers. The average consumption over the period from August 29 to November 15, 1997 was 117.8 kWh/day.

Natural Gas Use

There are four devices that use natural gas in the building. There is a boiler which heats a glycol mixture which is used to heat the incoming air supply, two boilers which heat water for the radiant floor heating system on floors 2,3, and 4, and the baseboard heating on floor 1, and a natural gas fired domestic water heater. Each of these natural gas devices is submetered using separate natural gas meters.

The natural gas meter for the glycol heater proved to be defective, and was replaced in December of 1997.

Plots of the natural gas consumption for the three devices which were sub-metered are shown in figures 8, 9, and 10. The natural gas consumption is plotted as a function of the heating degree-day/day values. To date, there were only 6 points available per plot. As more data is accumulated, the curves will show a more definitive trend. Boiler number 2 showed considerably higher consumption than boiler number 1. The thermostats for these boilers are set in such a way that boiler number 2 provides the bulk of the heating until the building. For boiler number 2, the natural gas consumption at the low degree day values seems very erratic. This phenomenon is due to the problems the building experienced with temperature control during the milder weather. The indoor air temperature varied from a low of 21.4 C to a high of 28.3 C during the month of September, in part because of problems with temperature control in the building.

Heating Degree Days

The heating degree day values for the months from August 1997 to December 1997 were as follows:

Month	1997 Values Heating Degree Days (base 18 C) C- days	Long Term Average Heating Degree Days (base 18 C) C- days
August	56.2	81.7
Sept	164.4	243.6
Oct	463.9	444.1
Nov	682.1	767.9
December	744.7	1085.8
Totals	**2111.3**	**2623.1**

As can be seen from the table, the months from August through Decebmer were considerably warmer than the long term average values. It is believed that the strong El Nino phenomenon is primarily responsible for the warmer temperatures experienced in 1997.

Work Plan

1. The indoor air quality monitoring will be done in February 1998 in the suites.

2. The data logging will continue until Fall, 1998.

3. Meter readings and rainfall wetting patterns will continue until Fall, 1998.

4. The next monitoring report will be provided by April 30, 1998.

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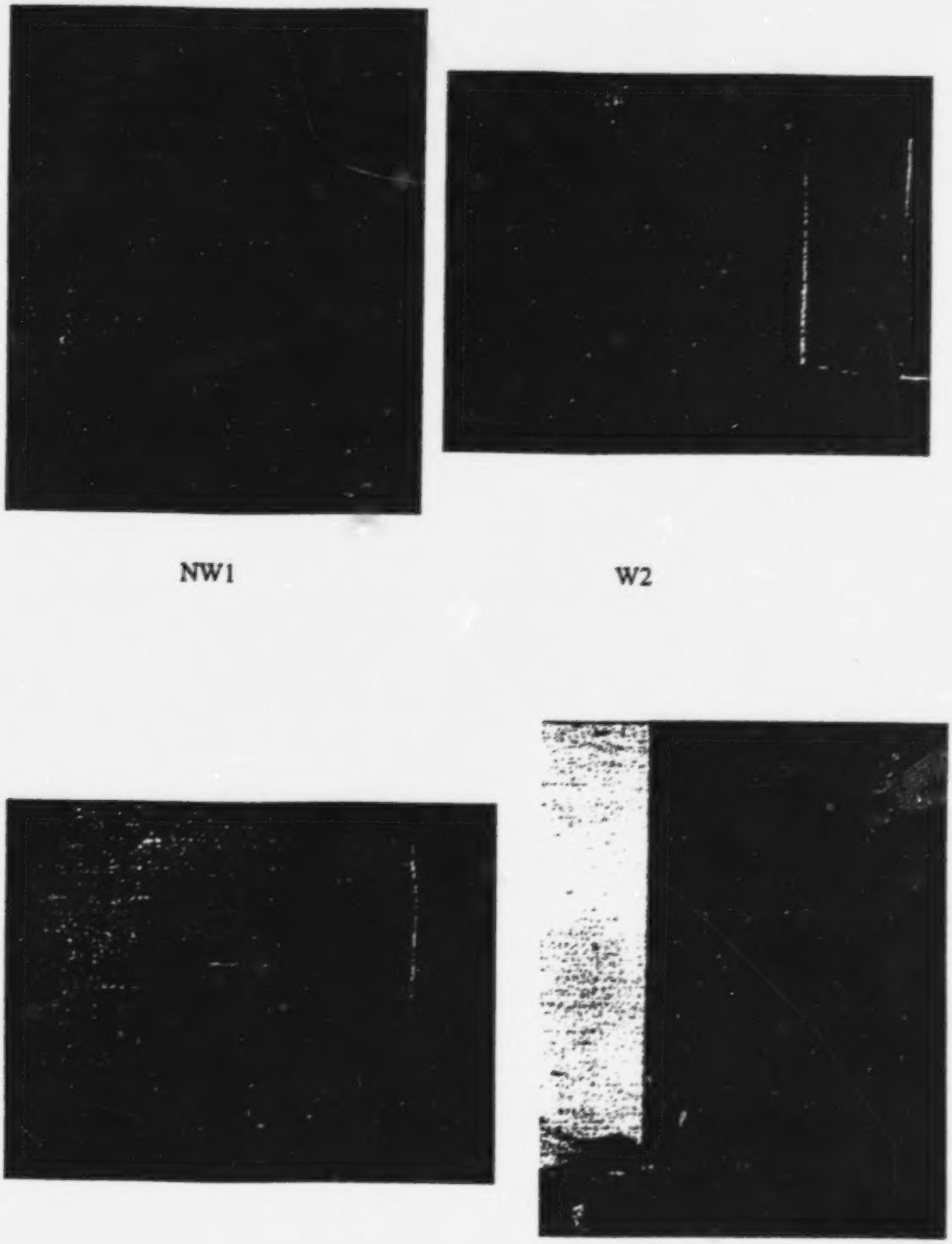
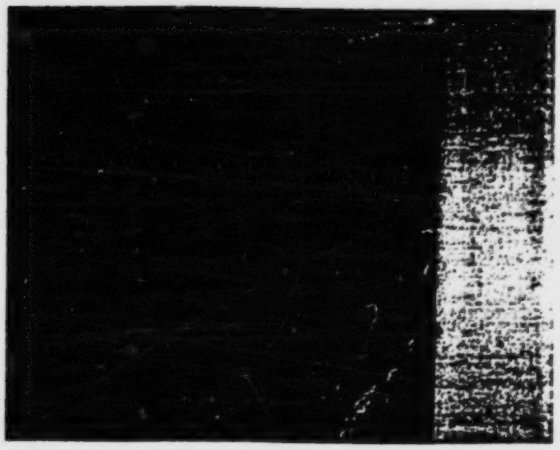


NW1 W2

E3 SE4

Figure 1. View of walls where heat flux transducers are located



N4

NW4

Figure 2. View of walls where heat flux transducers are located.

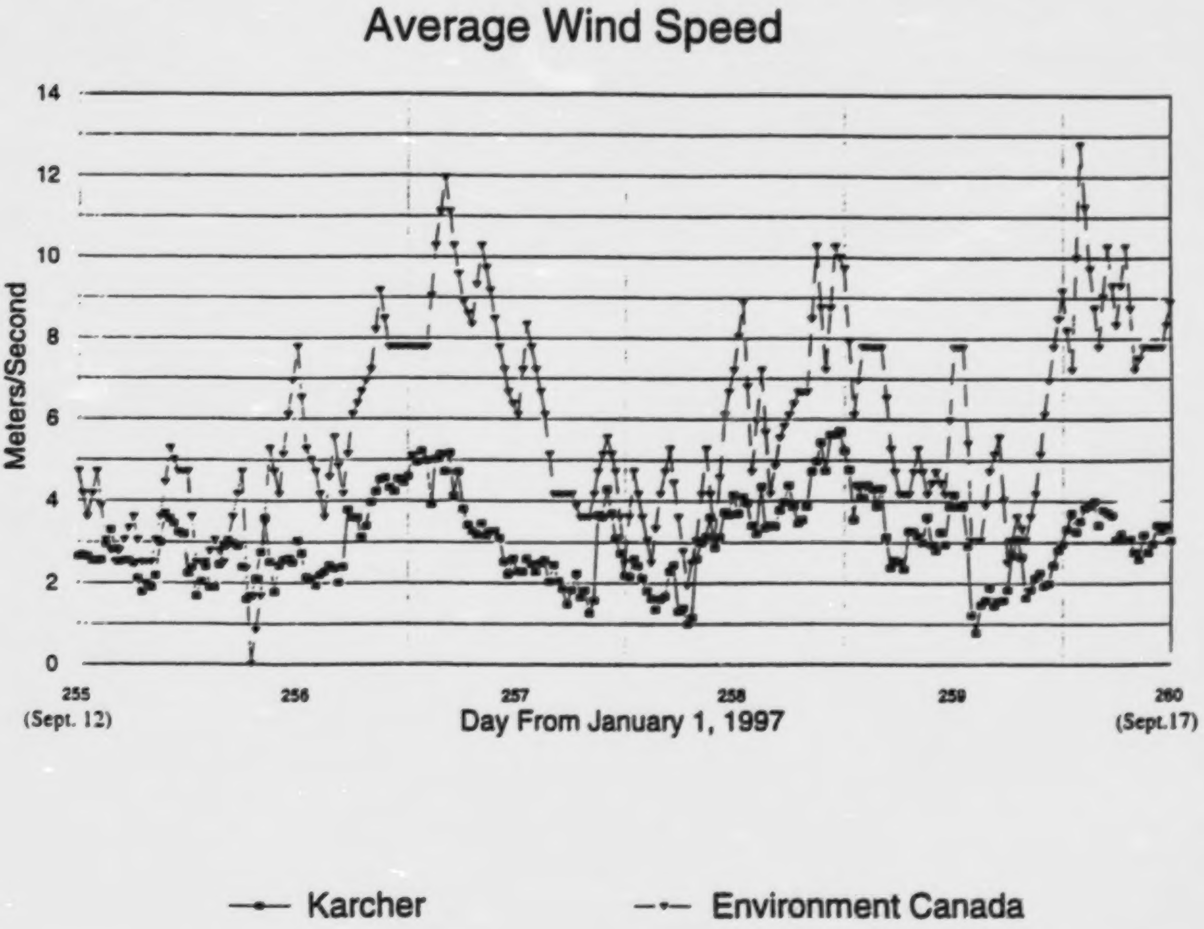


Figure 3. Wind Speed Comparison

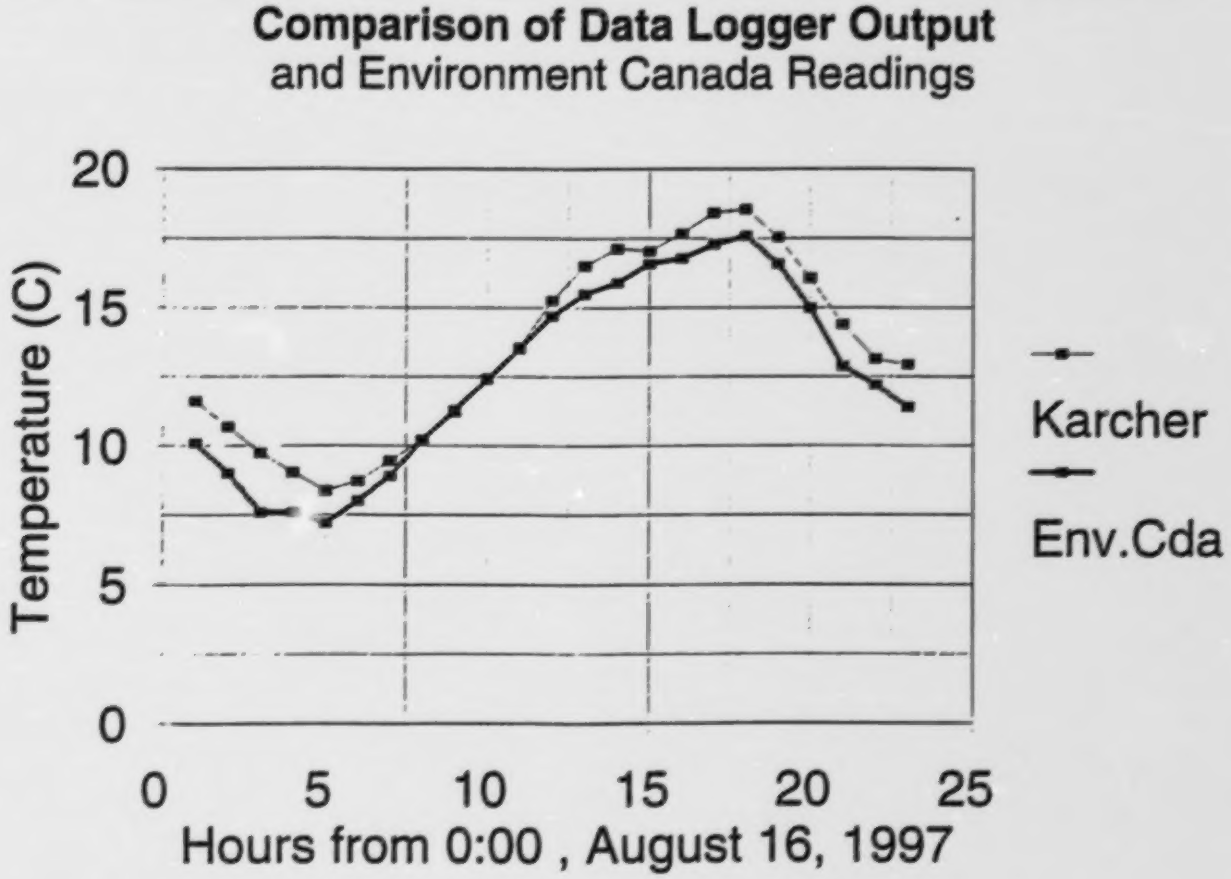


Figure 4. Comparison of temperatures measured at the apartment building and at the Environment Canada weather station

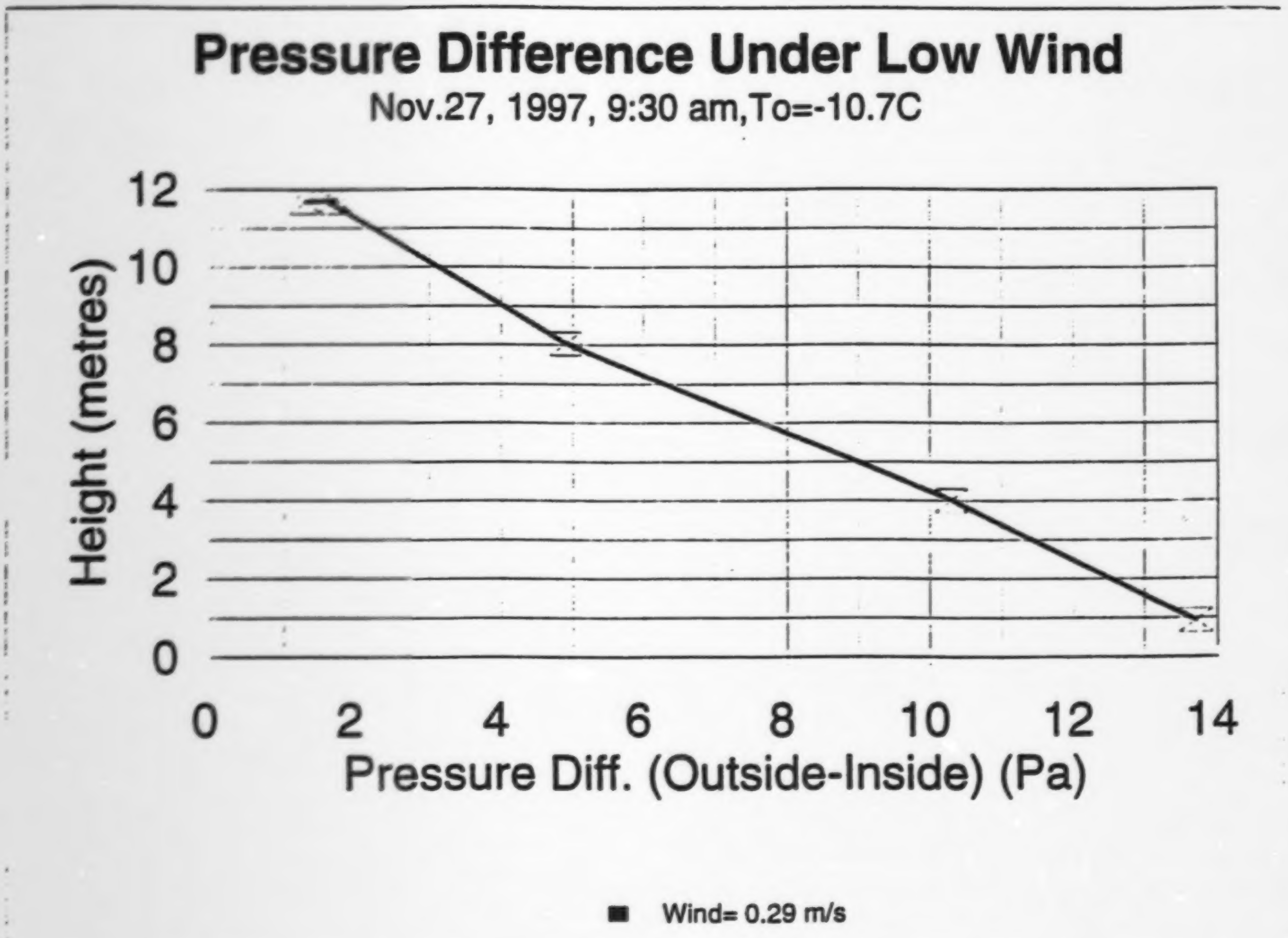


Figure 5. Pressure differences measured across the building envelope during low wind conditions

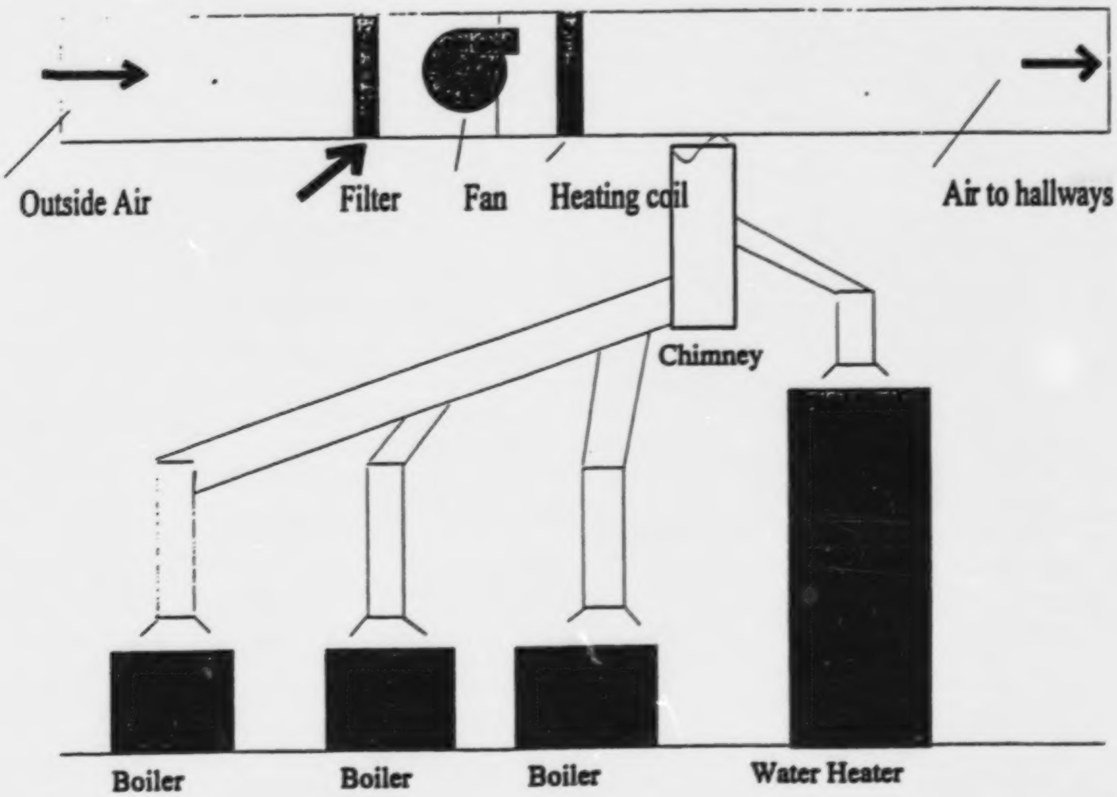

Outside Air
Filter
Fan
Heating coil
Air to hallways
Chimney
Boiler
Boiler
Boiler
Water Heater

Figure 6. Mechanical room layout showing leakage into supply air fan

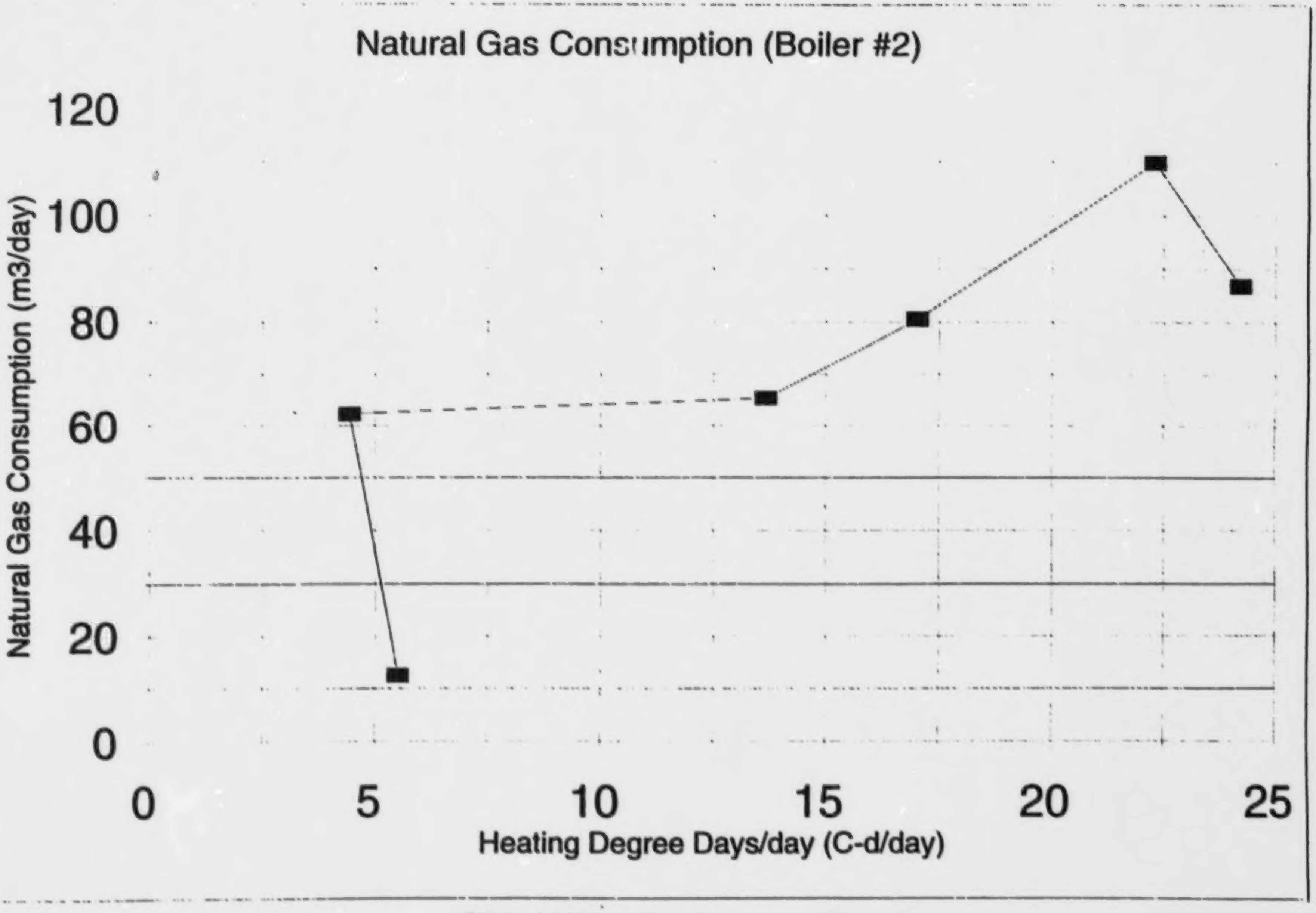


Figure 9. Natural gas consumption of boiler #2

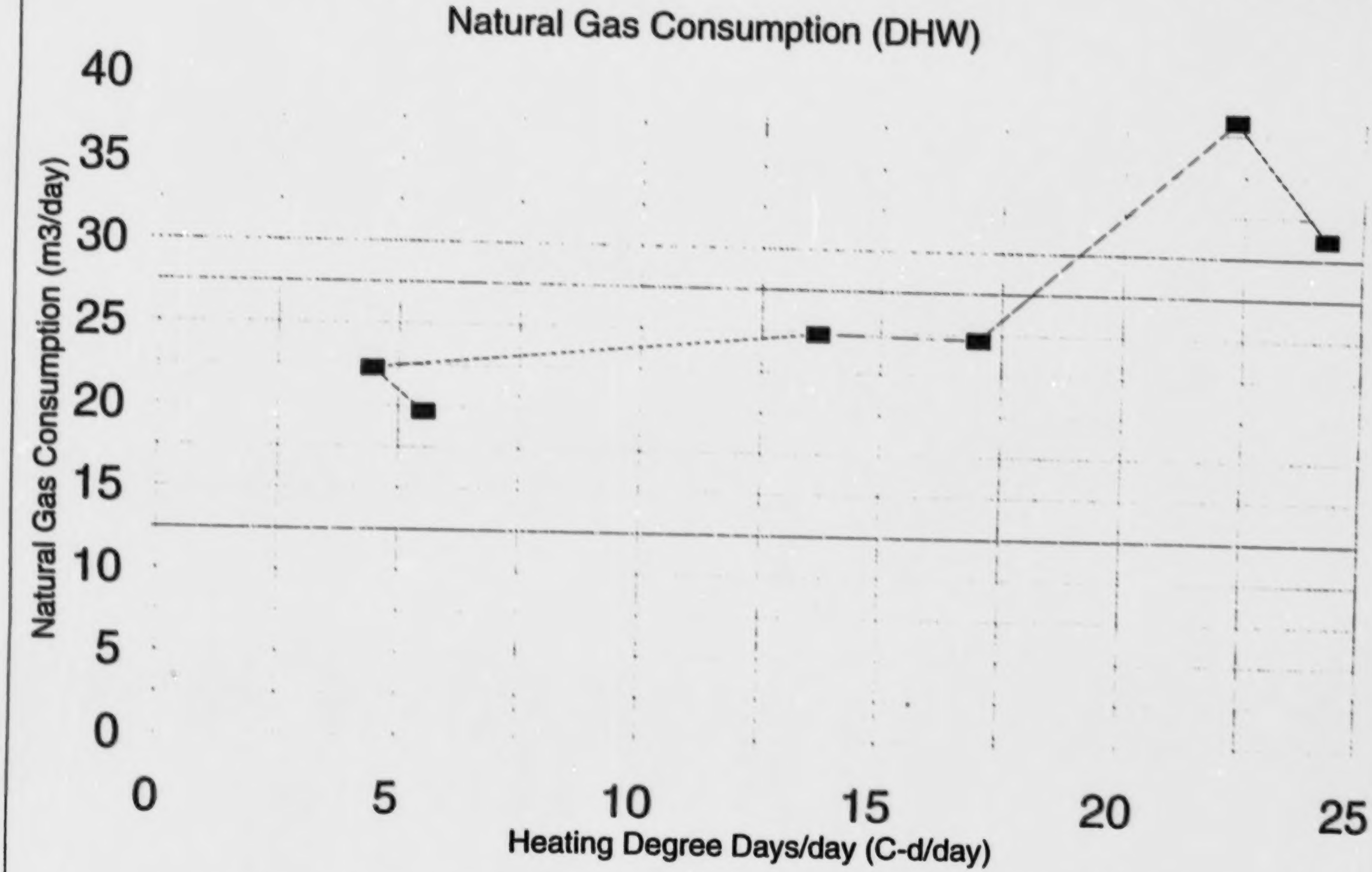


Figure 10. Natural gas sumpton of domestic water heater

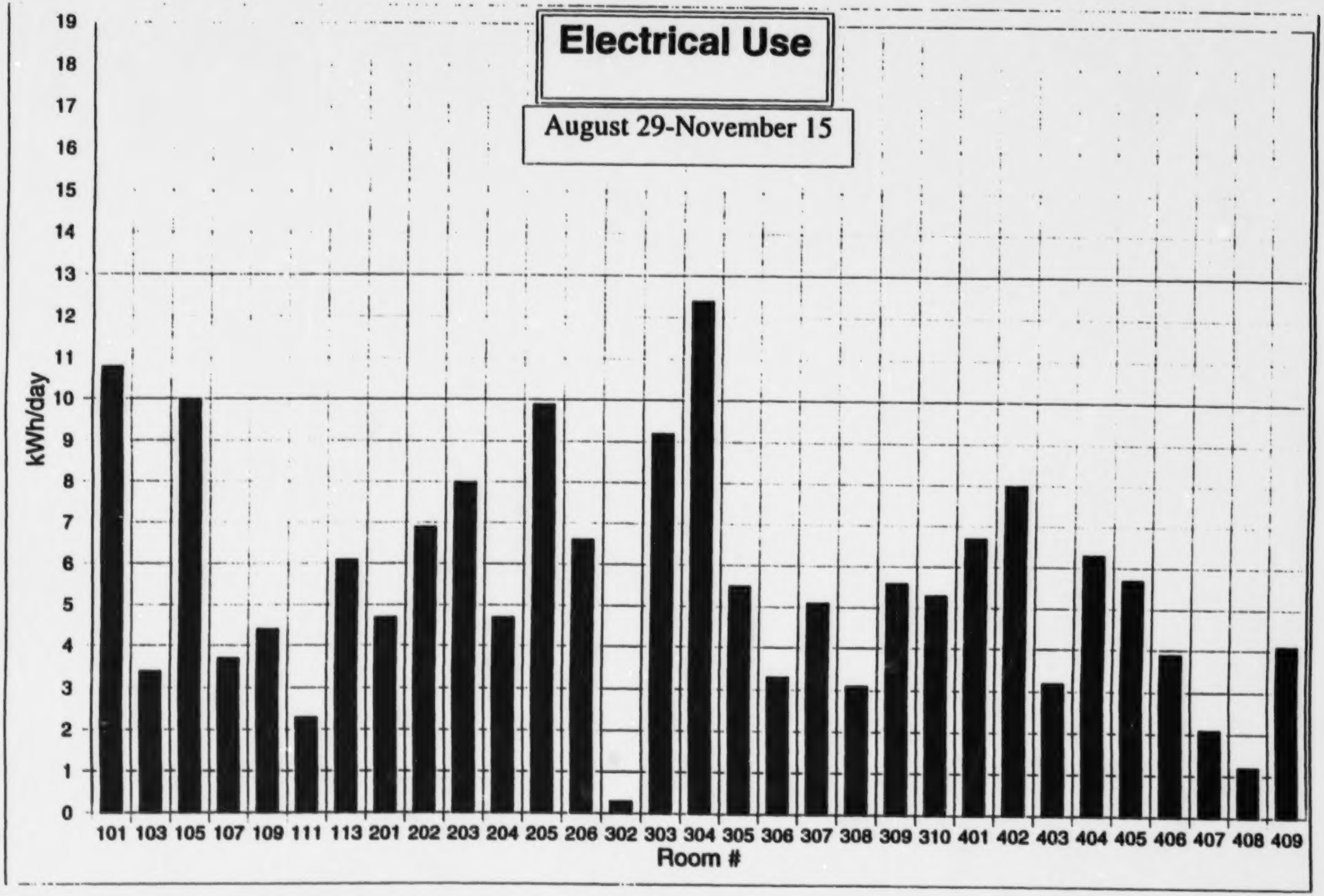


Figure 7. Bar graph of electricity consumption

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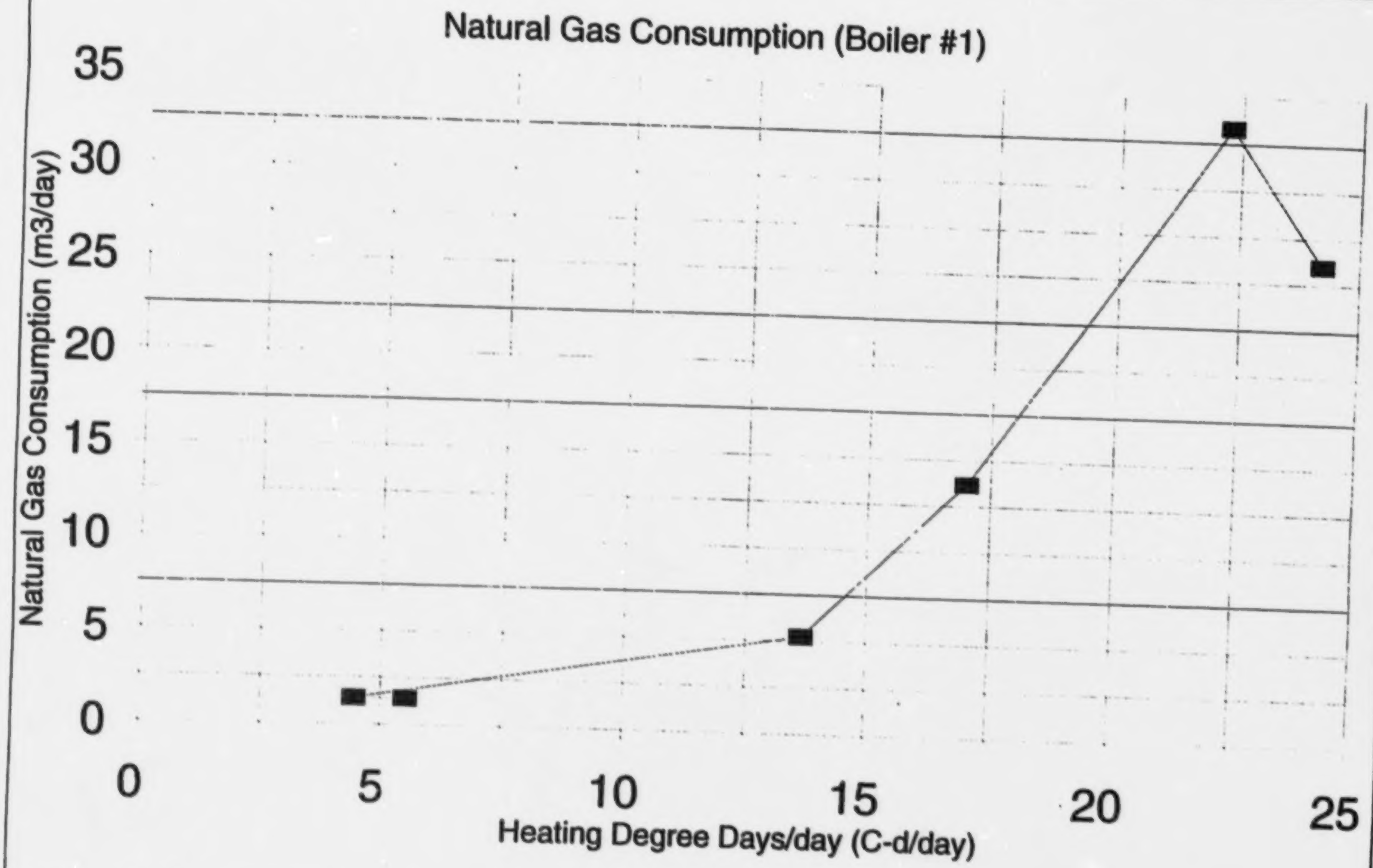

Figure 8. Natural [illegible] consumption of boiler # 1

CONFIDENTIAL REPORT

Interim Report #4
The Renovation of an Apartment Building with Solid Masonry Walls

for

Innovation Centre for Highrise and Multiples
Canada Mortgage & Housing Corporation

by

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Building Performance

Small Industry Services

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SRC Publication No.
10316-1C98

June 1998

As was mentioned earlier, the temperature in the exhaust at the second floor tends to be relatively constant and this relationship is shown in Figure 8. This temperature is somewhat higher than the value of approximately 22°C which is often found in buildings. A number of the suites have experienced some difficulties with the radiant floor temperature controllers. As a consequence, these suites tend to be somewhat overly heated.

2.9 Absolute Humidity N4 Cavity

The absolute humidity was calculated using the relative humidity and temperature in two of the wall cavities. The sensors are located in the exterior walls between the wood stud wall and the brick wall. For the location N4, which is on the north wall on the fourth floor, the value of the absolute humidity in the cavity is plotted in Figure 8. This absolute humidity in general terms tends to mimic the absolute humidity outdoors as shown in Figure 3 although there are some moisture storage effects present due to the brick.

2.10 Absolute Humidity in the Cavity for SE4

The absolute humidity in the cavity for SE4 (Figure 10) again tends to mimic the absolute humidity in the air outside, although with some smoothing because of the effect of the moisture storage in the brick. The absolute humidity in the SE4 wall cavity is higher than that found in the N4 cavity (Figure 9). The SE4 location is where the moisture penetration test of the wall using a spray rack was conducted in August 1996. The N4 location had a peak absolute humidity of 11.2 g/kg air; the SE4 location had a peak absolute humidity of 14.7 g/kg air.

2.11 Onysko Sensor of Moisture Content in the SE4 Brick Wall

A plot of the Onysko Sensor moisture content for the SE4 brick wall versus time is shown in Figure 11. This sensor is imbedded about 1 brick width into the wall measured from the inside of the brick wall. This was the wall in which the moisture penetration test was conducted in August of 1996. There is a relatively small amount of drying occurring in this particular wall. It is interesting to note that at day 366 the moisture content falls greatly because of the temperature change in the building. Part of this change is due to the fact that the moisture sensor itself is temperature sensitive.

A temperature correction will be applied to this sensor in the next report.

2.12 Pressure Differences Across the Walls

In Figure 11 there is a plot of the pressure difference vs. time across the two elements of the wall at the NW1 location (northwest corner of the first floor). The red line represents the brick wall pressure difference and the green line represents the stud wall pressure difference.

On the right-hand side of the graph it can be seen that the average pressure difference across the stud wall is approximately 5 pascals and the pressure difference across the brick wall on average is approximately 12 pascals. The total pressure difference across the wall is the sum of the two pressure differences; thus, in the period from day 380 to 390 the total pressure difference would be approximately 17 pascals. This NW1 sensor is located near ground level. The reason there is such a high pressure difference across the wall is that the building is under relatively strong negative pressure caused by the mechanical ventilation system. There is approximately 2120 cfm of exhaust flow in the building and 1650 cfm of supply flow. As a consequence a fairly strong negative pressure is created in the building.

In Figure 11 a positive pressure difference indicates a positive pressure of the outdoors with respect to the indoors. In other words the air is infiltrating the building at this location.

It can also be seen from Figure 11 that almost all of the wind pressure fluctuations are damped by the exterior brick portion of the wall. Very little pressure fluctuation is seen across the stud wall.

2.13 Pressure Difference Across the Fourth Floor Wall (N4)

In Figure 12 a time plot of the pressure difference across the walls is shown. There can be seen a peak pressure difference of approximately 34 pascals is reached on day 251. Although these sensors are on the fourth floor of the building, because of the strong negative pressure in the building the average pressure difference is near zero.

3.0 COMPUTER MODEL OF THE BUILDING

The HOT 2000 program was used to model the energy flows in the building. A special version of the HOT 2000 program was secured from Brian Bradley of UNIES Ltd. This special version allows one to use a larger interior volume, larger ventilation flows, and larger internal gains than the standard HOT 2000 program.

All of the physical dimensions were input for the building; in addition, the internal heat gains from electrical use, from people, and from the use of domestic hot water were used as inputs to the program.

The following table shows the percentage breakdown of the heat losses in the building as calculated by the computer program:

Table 1. HOT2000 Calculation of Annual Space Heating Loads
Building As Is (1998)
Total Annual Gross Space Heating Load (including ventilation, excluding boiler losses) = 1882 Gigajoules
Total Boiler Consumption for space heating, ventilation and dhw, including boiler losses=2224 GJ

Building Element	**Percentage of Gross Space Heating Load (%)**
Ventilation and Air Change	70.4
Ceiling	2.4
Walls above grade excluding windows & doors	14.8
Walls below grade	1.1
Basement floor perimeter	1.3
Basement floor centre	1.6
Windows	7.8
Doors	0.6
Totals	100

The ventilation load is a very high percentage of the gross space heating load at 70.4% (1324 GJ). Because this number is very high, a hand calculation was used to confirm the number. Assuming 6600 Celsius heating degree days, an air flow of 1170 L/s, and an air density of 1.2 kg/m^3, the net ventilation load comes to 801 GJ. (As the degree-days are base 18 and not the actual temperature assumed in the computer calculation (21 C), the hand calculation should be increased by about 200 days times 3 degrees C (600 C-days). This would increase the net ventilation hand calculation to about 874 GJ. The difference between 1324 GJ and 874 GJ (a difference of 450 GJ) is the computer model's calculation of exfiltration.

3.1 Heat Gains as Calculated by the Computer Model

The heat gains for the building are as follows:

Table 2. Building Heat Supplies for Space Heating: (Karcher As Is--1998)
HOT-2000 Calculation
Total=1882 GJ

Usable Internal Gains	17.1%
Usable Solar Gains	4.5%
Heat Supplied by Boilers	78.4%
Total	100%

The solar gains are relatively low because of the small window areas on the south side, large windows on the north, and modest window areas on the east and west.

The computer model was run using several different scenarios.

The results are presented in Table 3.

Table 3. HOT-2000 Calculations Using Varying Assumptions

Building Assumption	Design Heat Loss (kW)	Average Annual Air Change Rate (ac/h)	Gross Annual Space Heat Load (excluding boiler losses) (GJ)	% of heat loss associated with ventilation and natural air change
As is (1998)	200	1.08	1882	70.4
As is but no mechanical ventilation	120	0.376	1077	48.1
As is but with balanced ventilation at 775 L/s, (The current supply air flow)	178	0.884	1656	66.3

As is, tightened to R-2000 standard; 65% effective heat recovery on 775 L/s of balanced air flows	125	0.66	946	41.0

3.2 Comparison of computer model output with measured gas consumption

A comparison of the measured natural gas consumption of the building (ventilation boiler, two space heating boilers, and domestic water heater) with the output of the HOT-2000 analysis of the building was done. Inputs to the computer model included all the physical dimensions of the building along with the known internal heat gains from electrical use in the building and the efficiency of the boilers, and the known supply air and exhaust air flows. A plot of the monthly natural gas consumption of the building as calculated by the HOT2000 program is presented in figure 14.

As can be seen, the natural gas consumption is relatively linear with heating degree-days per day. Variations from month to month in the solar radiation availability and soil temperatures cause most of the non-linearity in the colder weather. The line does not pass through zero, as the domestic hot water consumption and the natural gas pilot light consumption is present in the warmer months.

In figure 15, the measured natural gas consumption for the building (meters on 3 boilers plus the water heater) water is plotted on the same graph. Because of a gas meter failure on the ventilation air boiler, only six points were available. The measurement period was from December 97 to March 98. The agreement is quite good.

4.0 Ventilation Standards

The CSA F326 Standard recommends a continuous exhaust flow of 30 L/s for a kitchen and 10 L/s for a bathroom. In the Karcher building, the measured exhaust flow per suite (30 suites) averages 39 L/s, which matches well the CSA total figure (40 L/s) for a dwelling with one kitchen and one bathroom. (The design flow per suite on the blueprints was 35 L/s)

The ASHRAE 62-89 Standard for Outdoor Air Requirements (Table 2.3) recommends 12 L/s continuous (or openable windows) for kitchens and 10 L/s (or openable windows) for a total of 22 L/s per suite.

With this wide disparity in standards (40 L/s [CSA F326] vs 22 L/s [ASHRAE]), it is little wonder that designers don't know what to choose.

5.0 Future Work

The following tasks will be completed for the final report:

1. Data logging will continue on the site until November 1998.
2. Manual energy readings every two weeks at the site will continue until November 1998.
3. Correction factors will be developed for the wood moisture sensors to account for the effect of temperature on the wood moisture content readings.
4. Samples of the stucco used on the building will be made and provided to IRC, NRC for their testing in July 1998.
5. A final report summarizing all the findings will be produced by December 31, 1998.

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Figure 1. Outdoor Temperature at Karcher Building

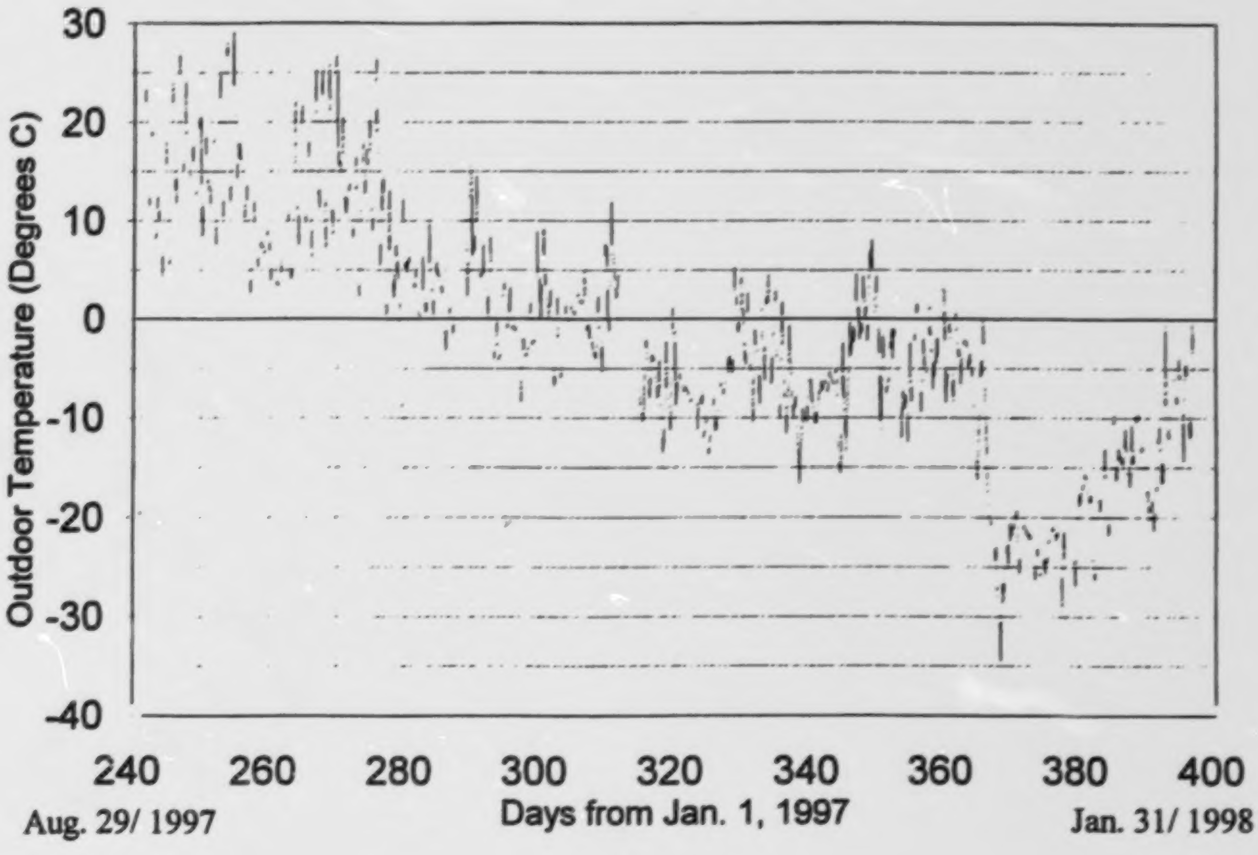


Figure 2. Outdoor Relative Humidity

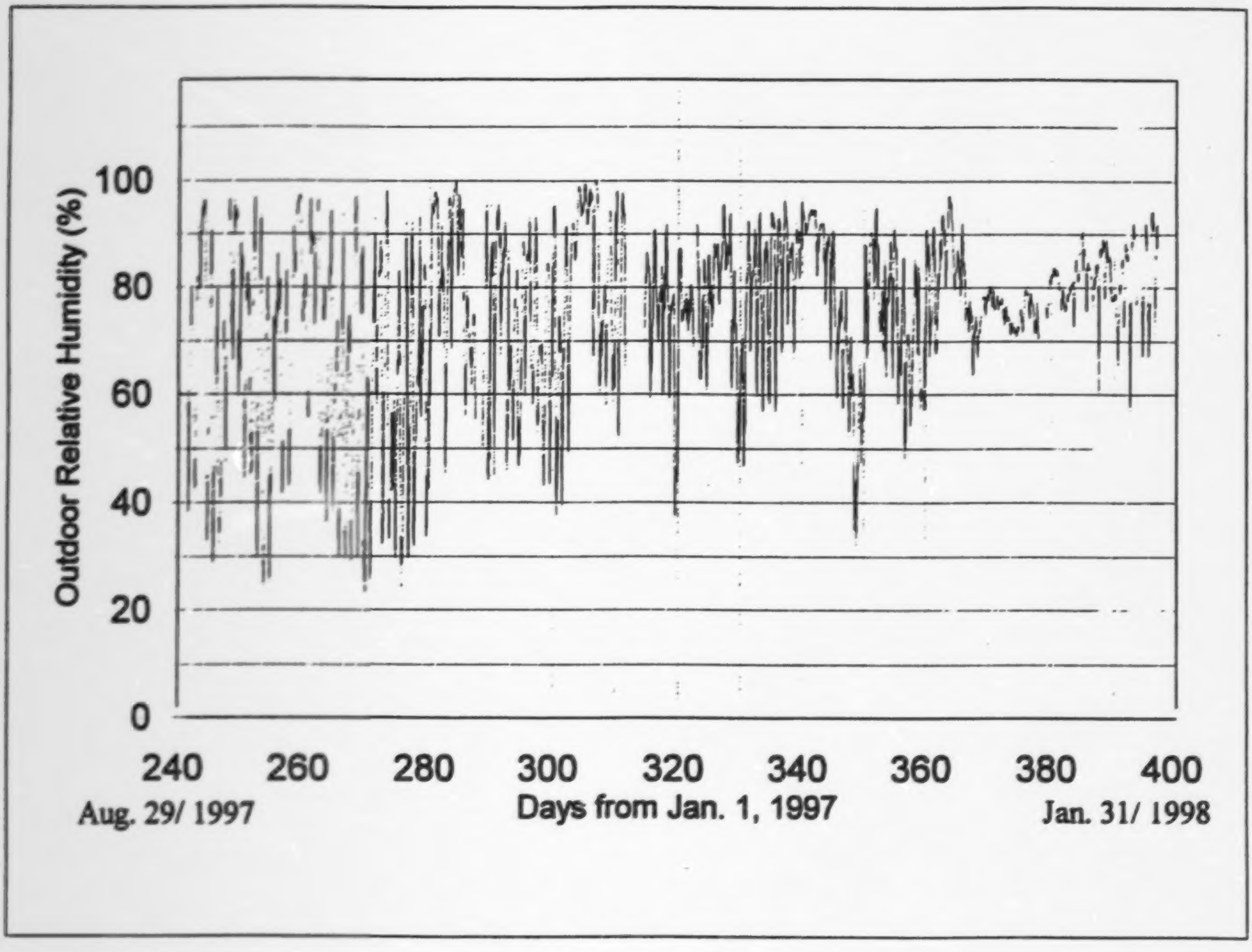


Figure 3. Outdoor Absolute Humidity

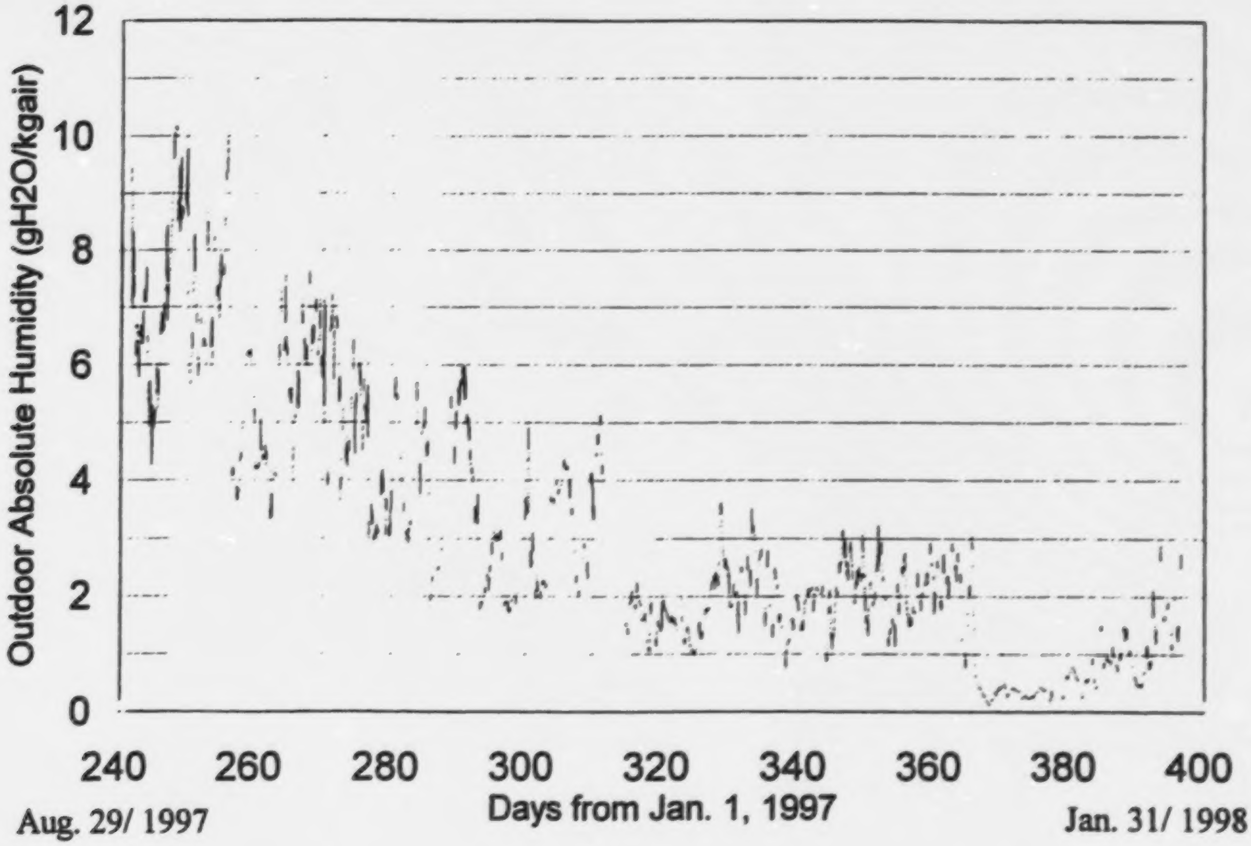


Figure 4. Second Floor Exhaust Relative Humidity

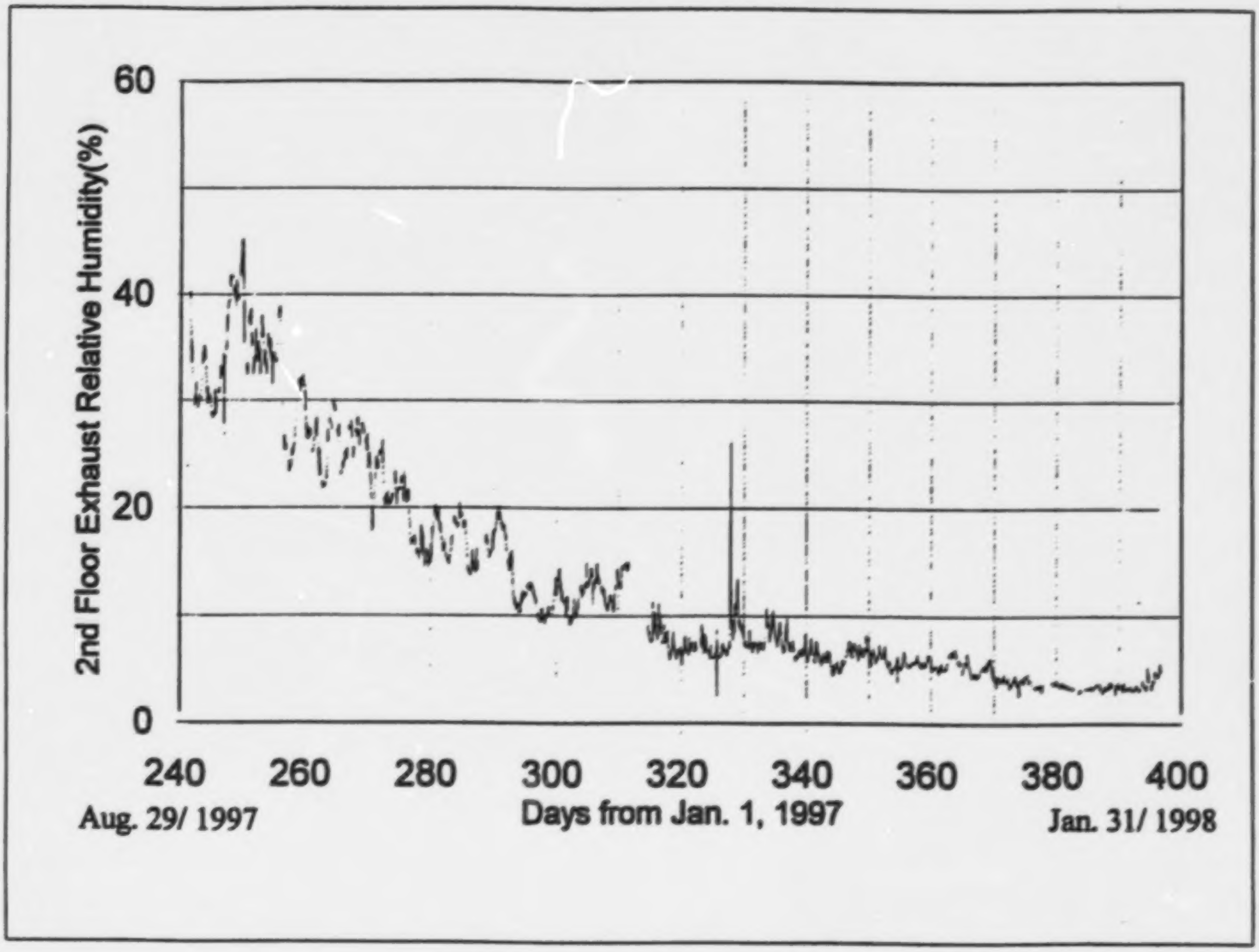


Figure 5. Second Floor Exhaust Absolute Humidity

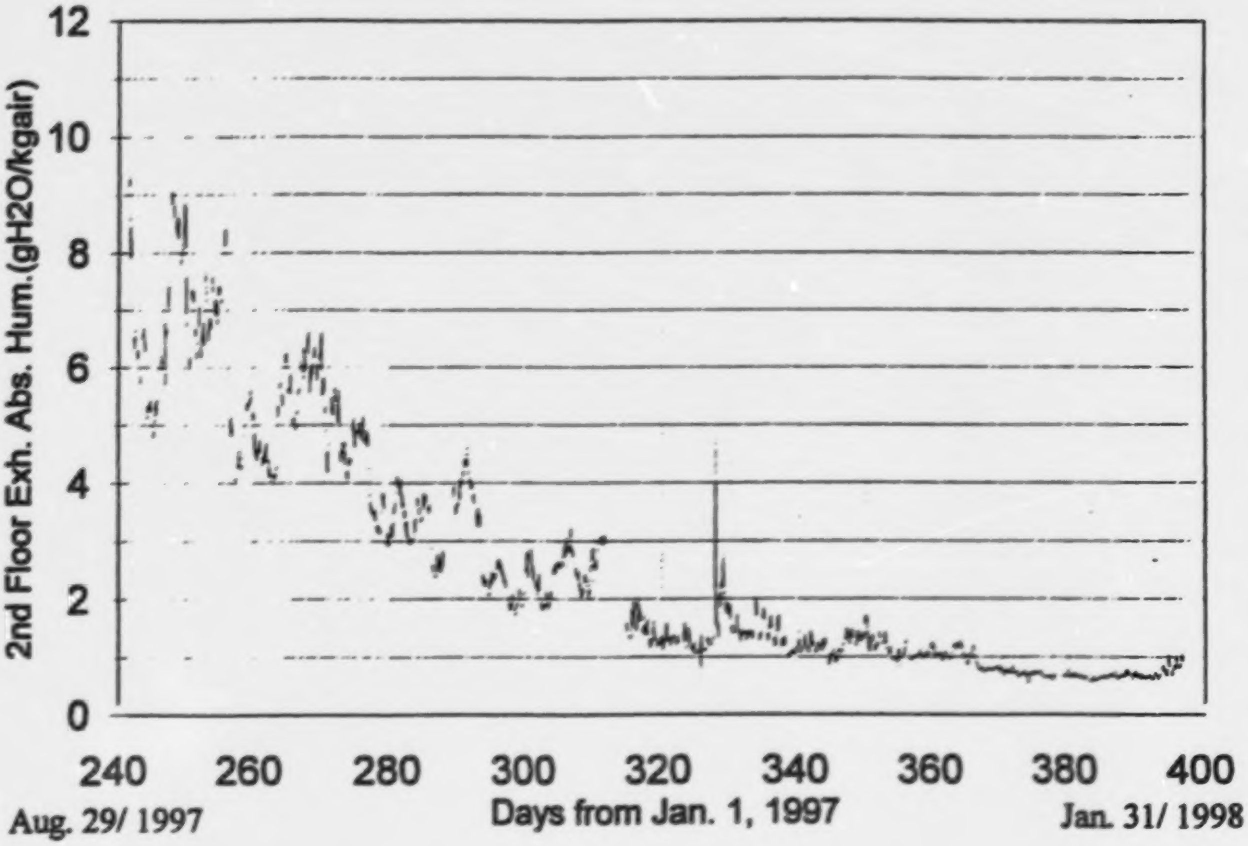


Figure 6. Comparison of Indoor and Outdoor Absolute Humidity Values

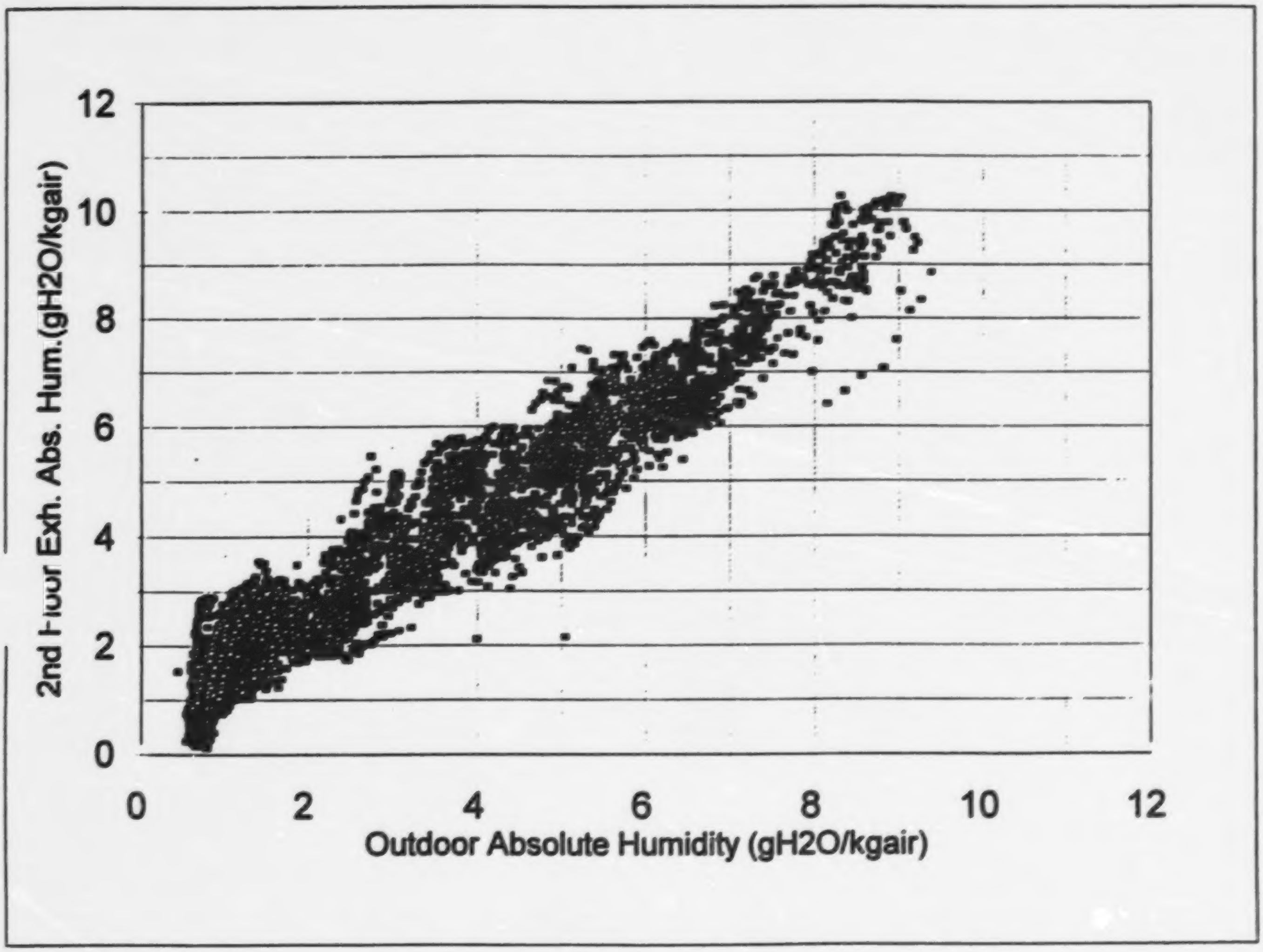


Figure 7. Comparison of Indoor and Outdoor Absolute Humidity Values

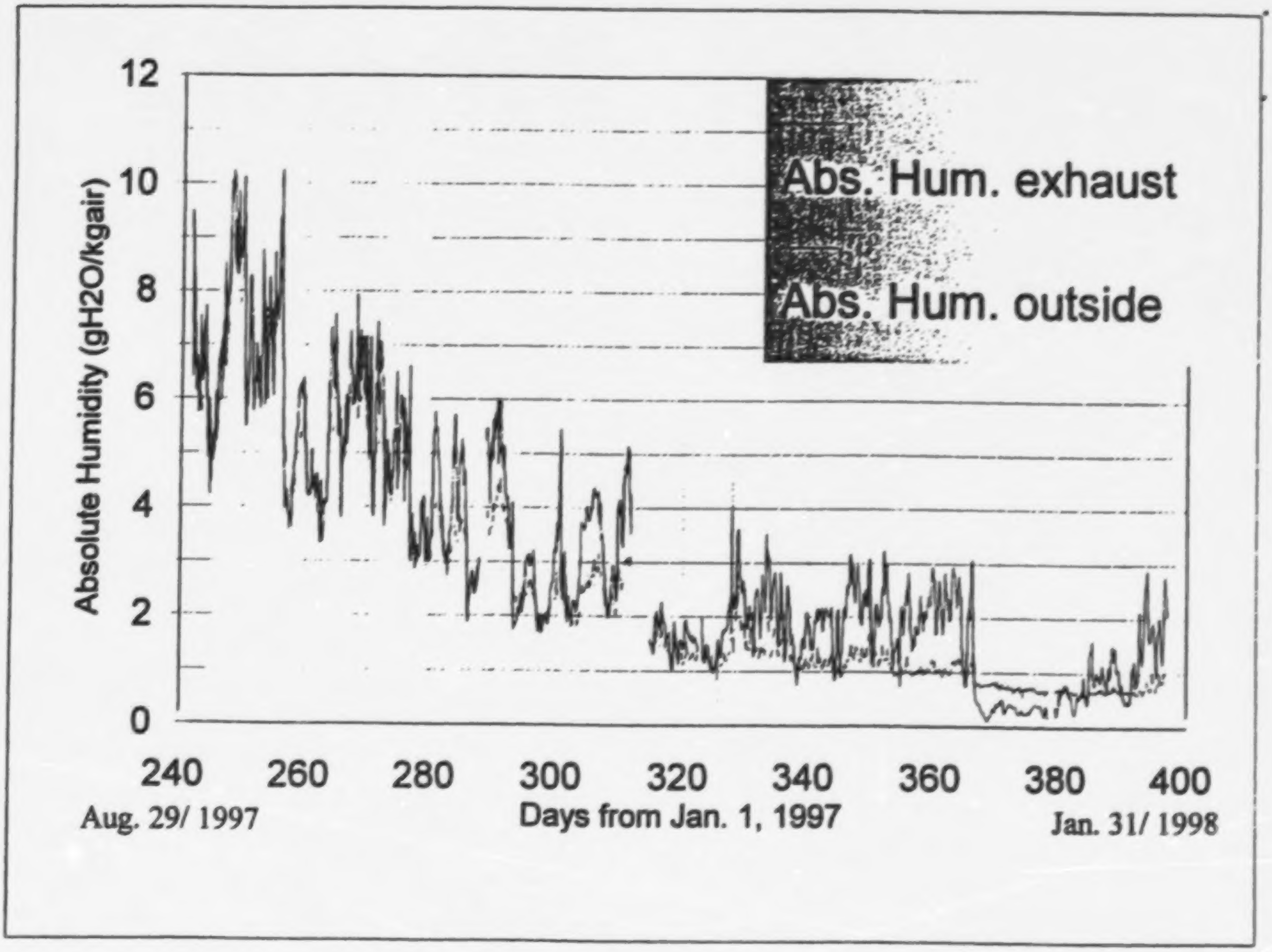


Figure 8. Exhaust Air Temperature in Second Floor Exhaust Duct

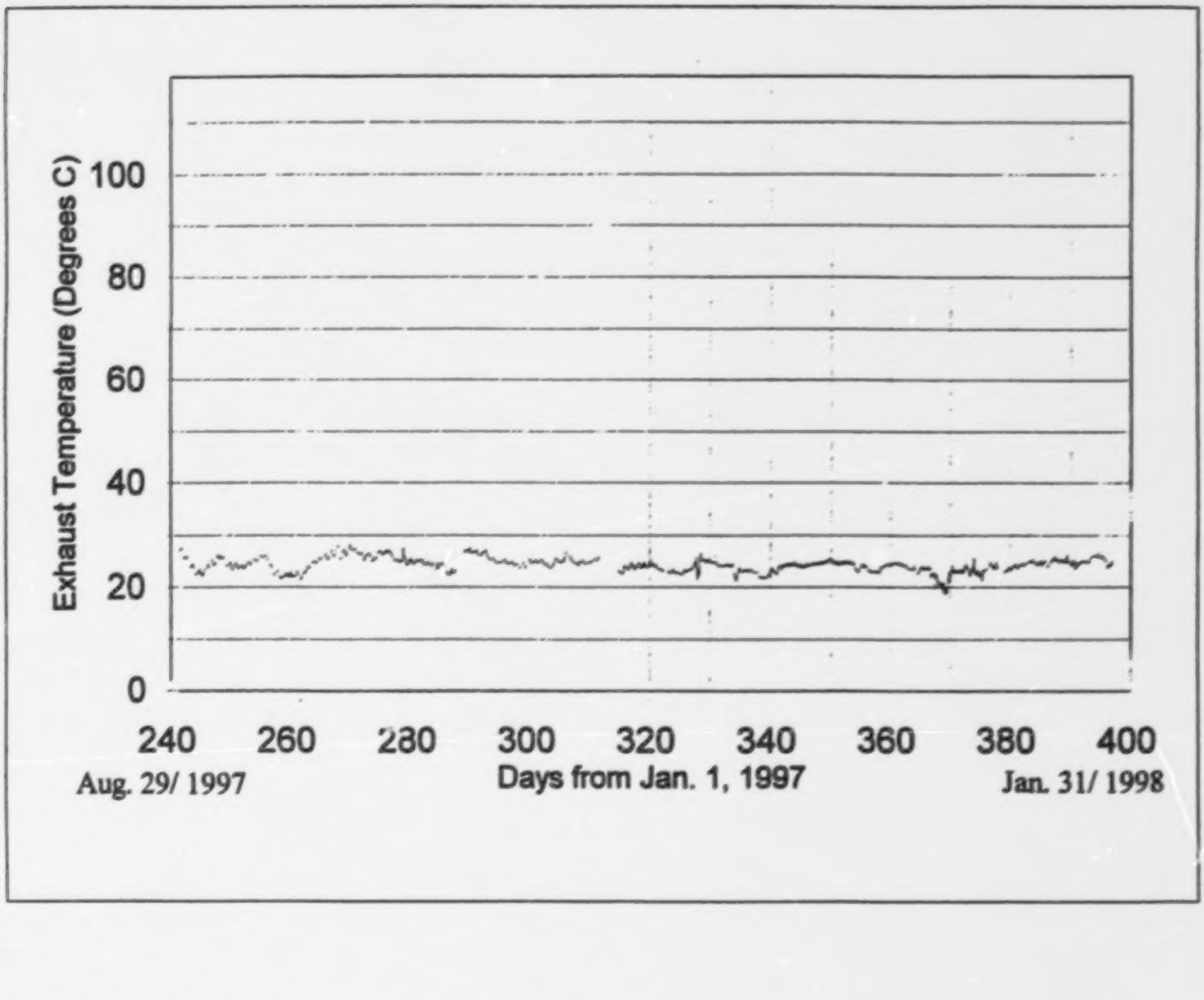


Figure 9. Absolute Humidity N4 Cavity

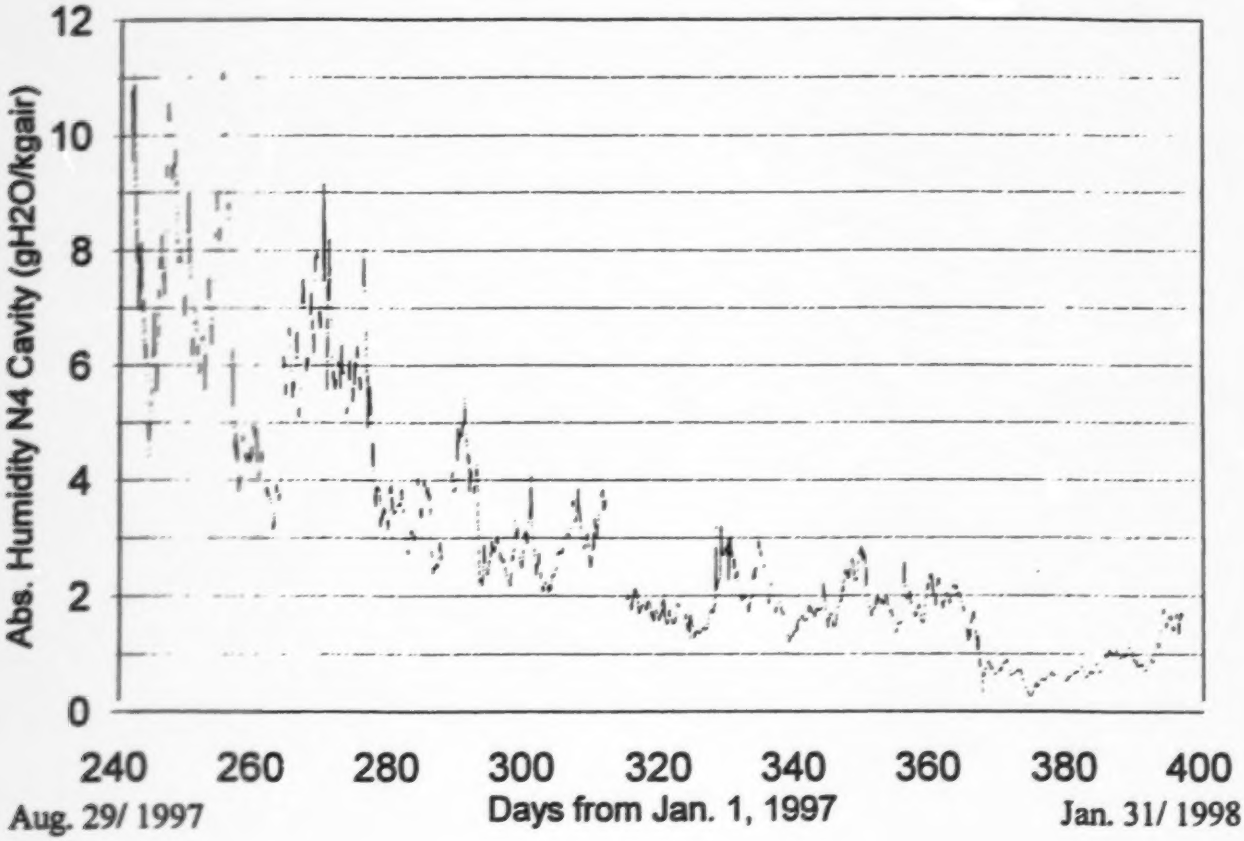


Figure 10. Absolute Humidity SE4 Cavity

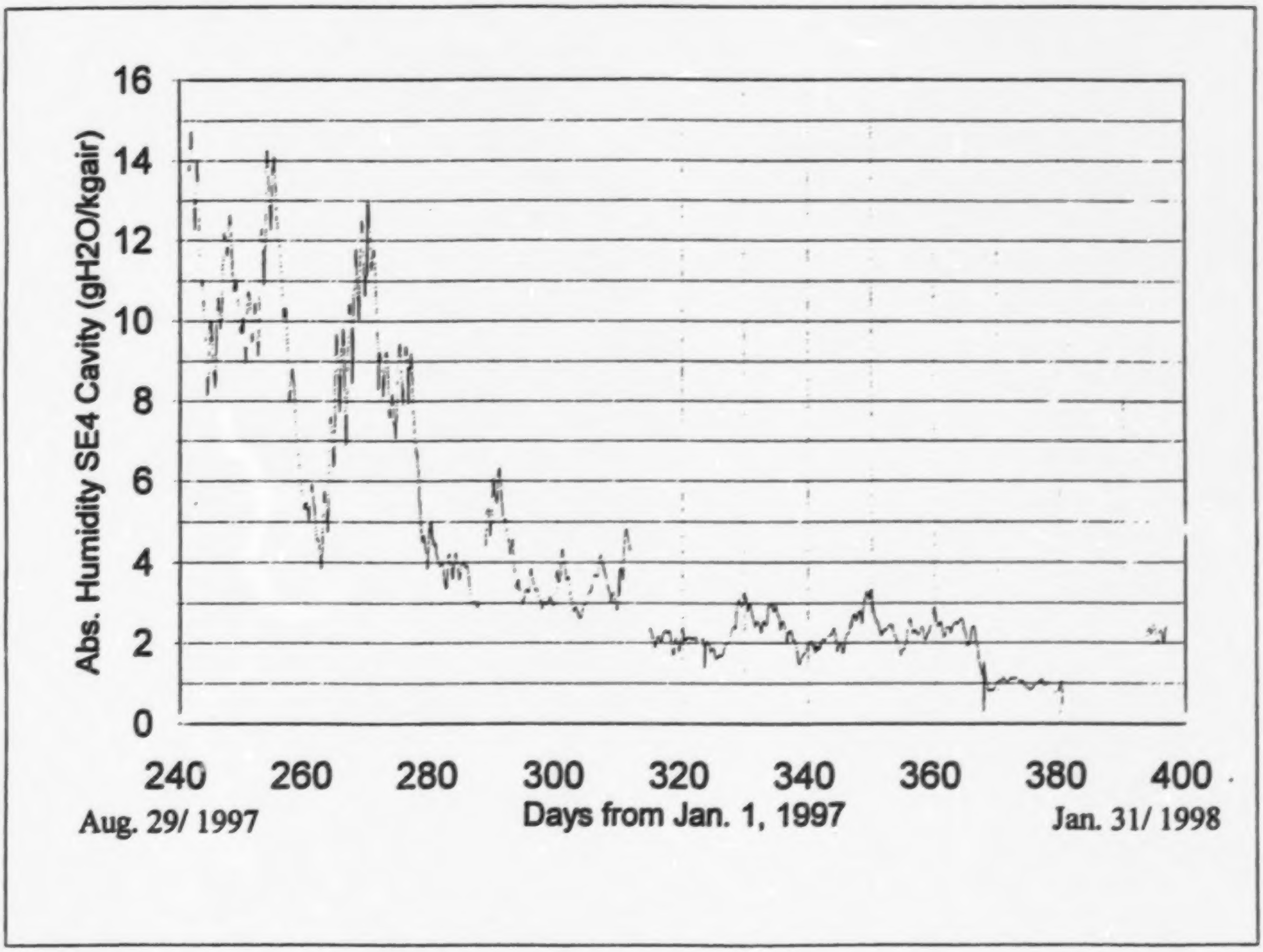


Figure 11. Onysko Sensor SE4 Moisture Content

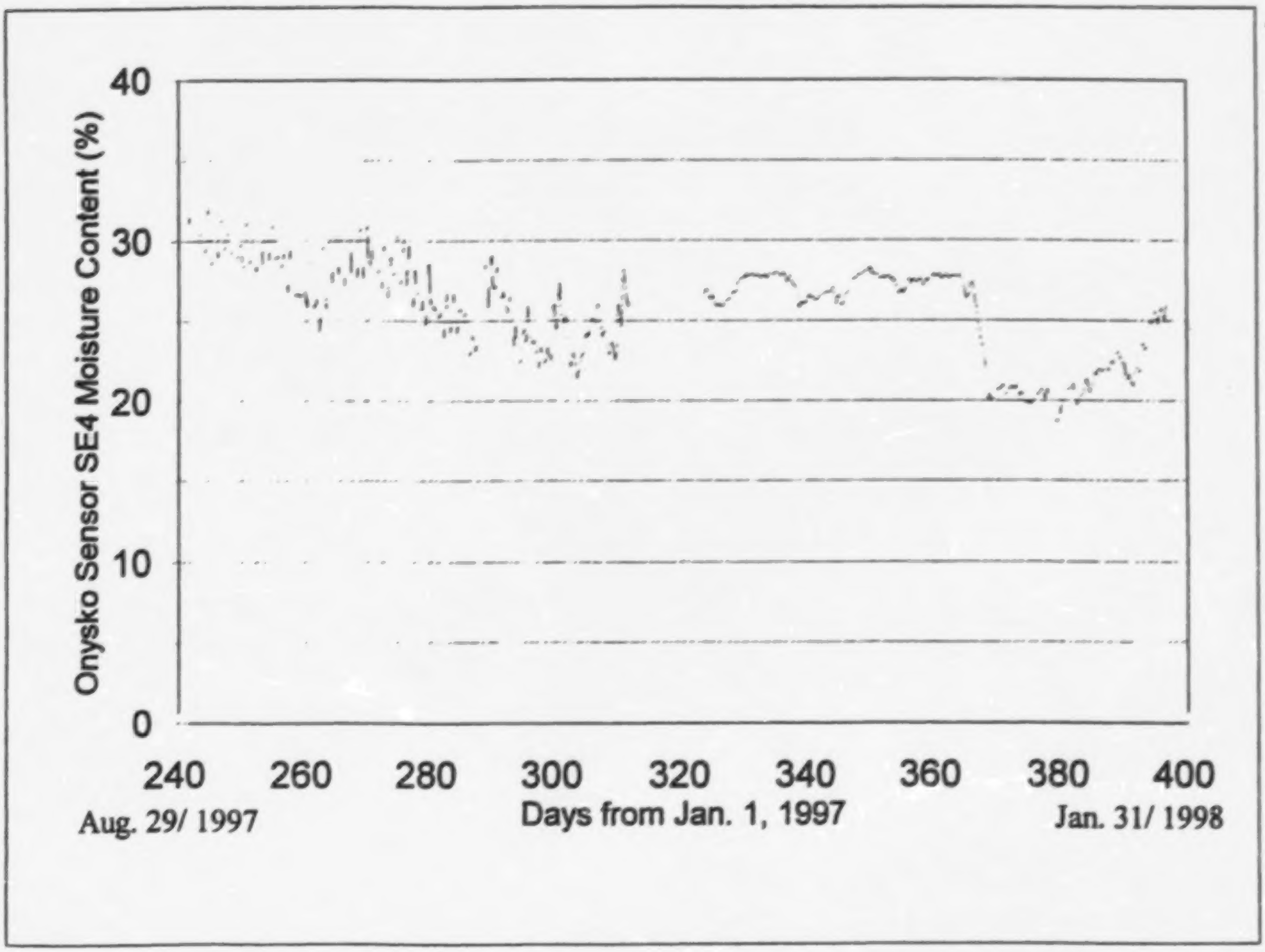


Figure 12. Pressure Differences at NW1 Wall Location

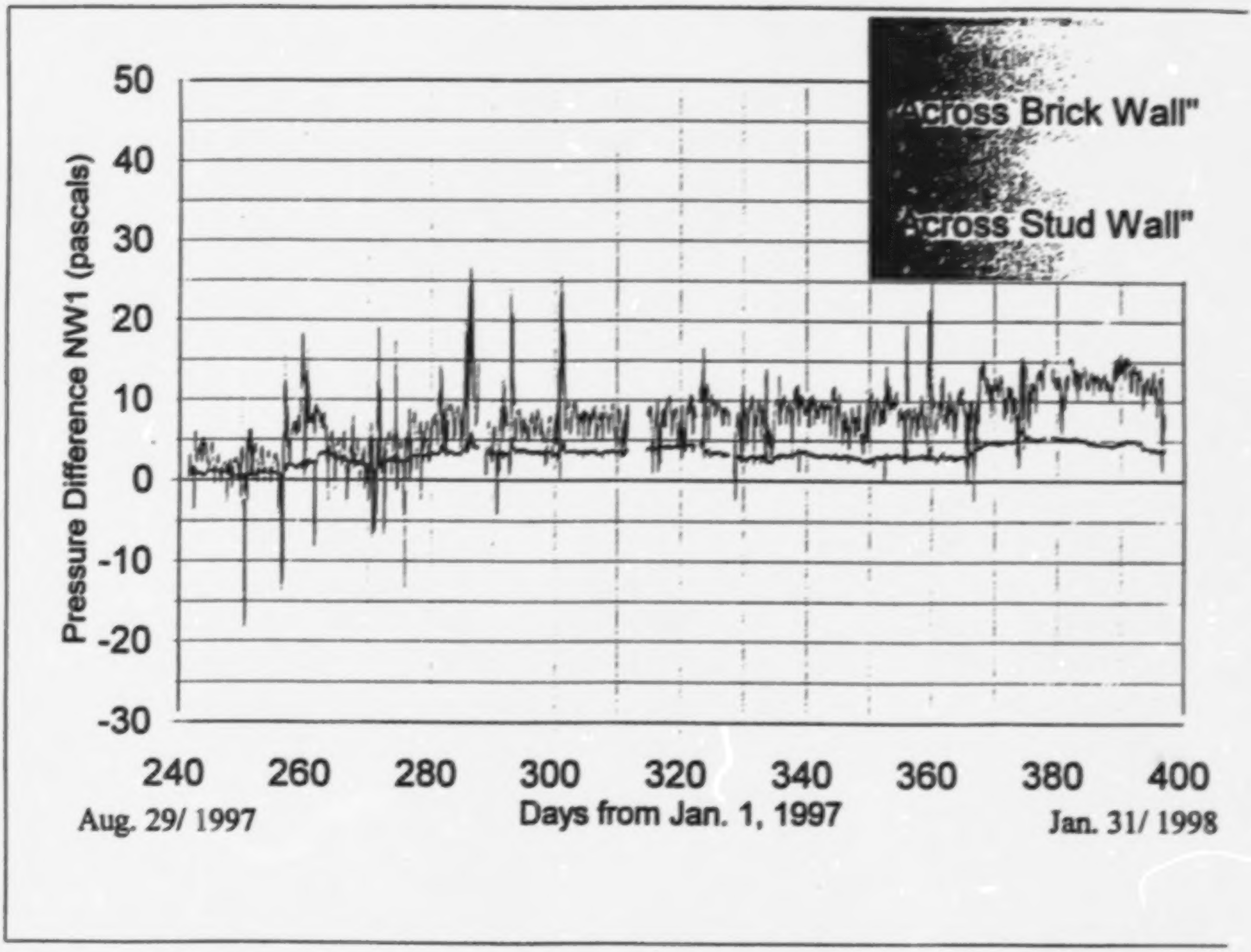


Figure 13. Pressure Differences at N4 Wall Location

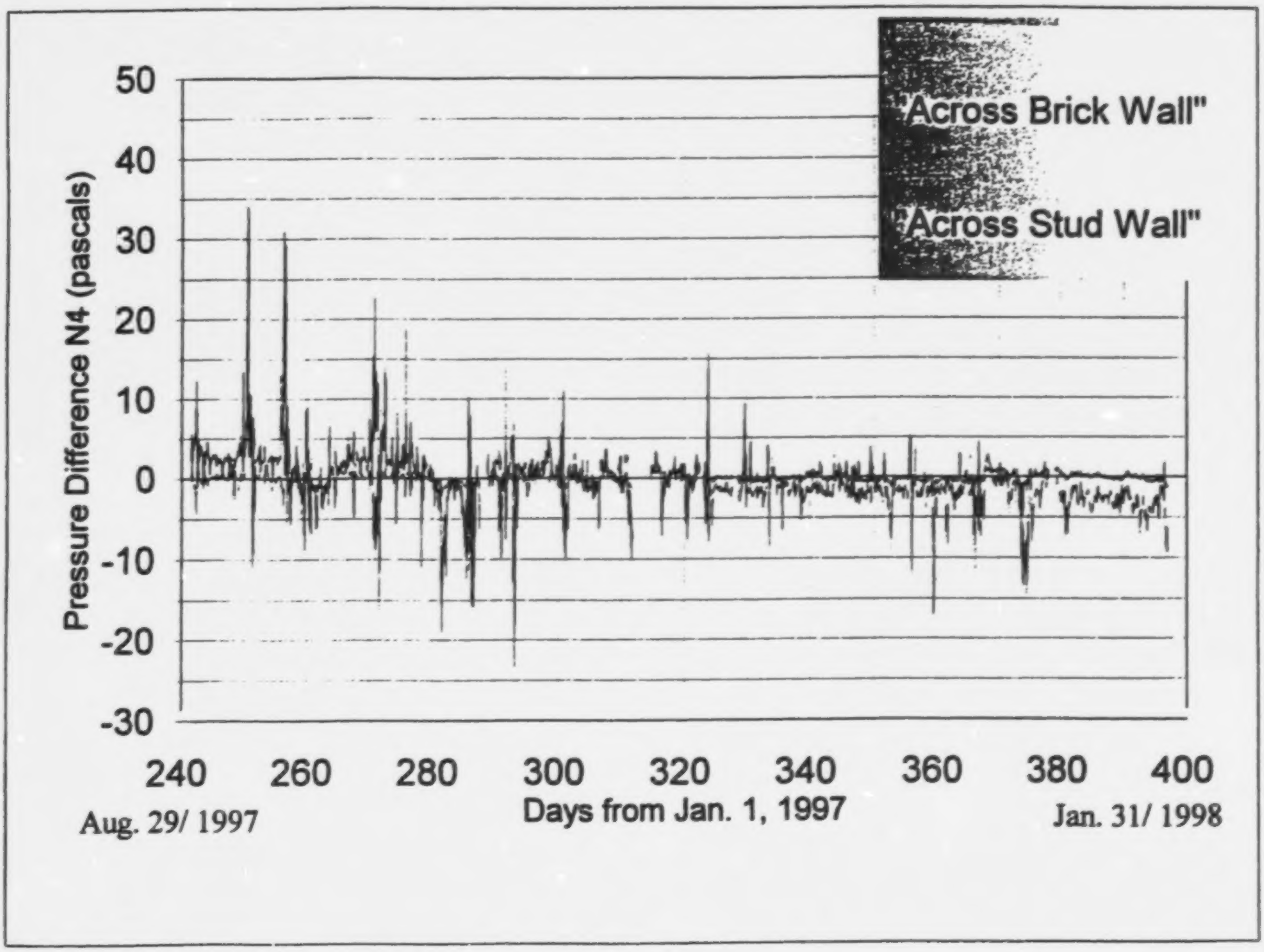


Figure 14. HOT2000 Computer Calculation of Total Natural Gas Consumption for Karcher.
Inputs: 1170 L/s exhaust intake flow; 775 L/s outside air flow
Room temperature of 22 °C in upper 3 floors; 22 °C in basement
1 m^3 gas = 37.3 MJ

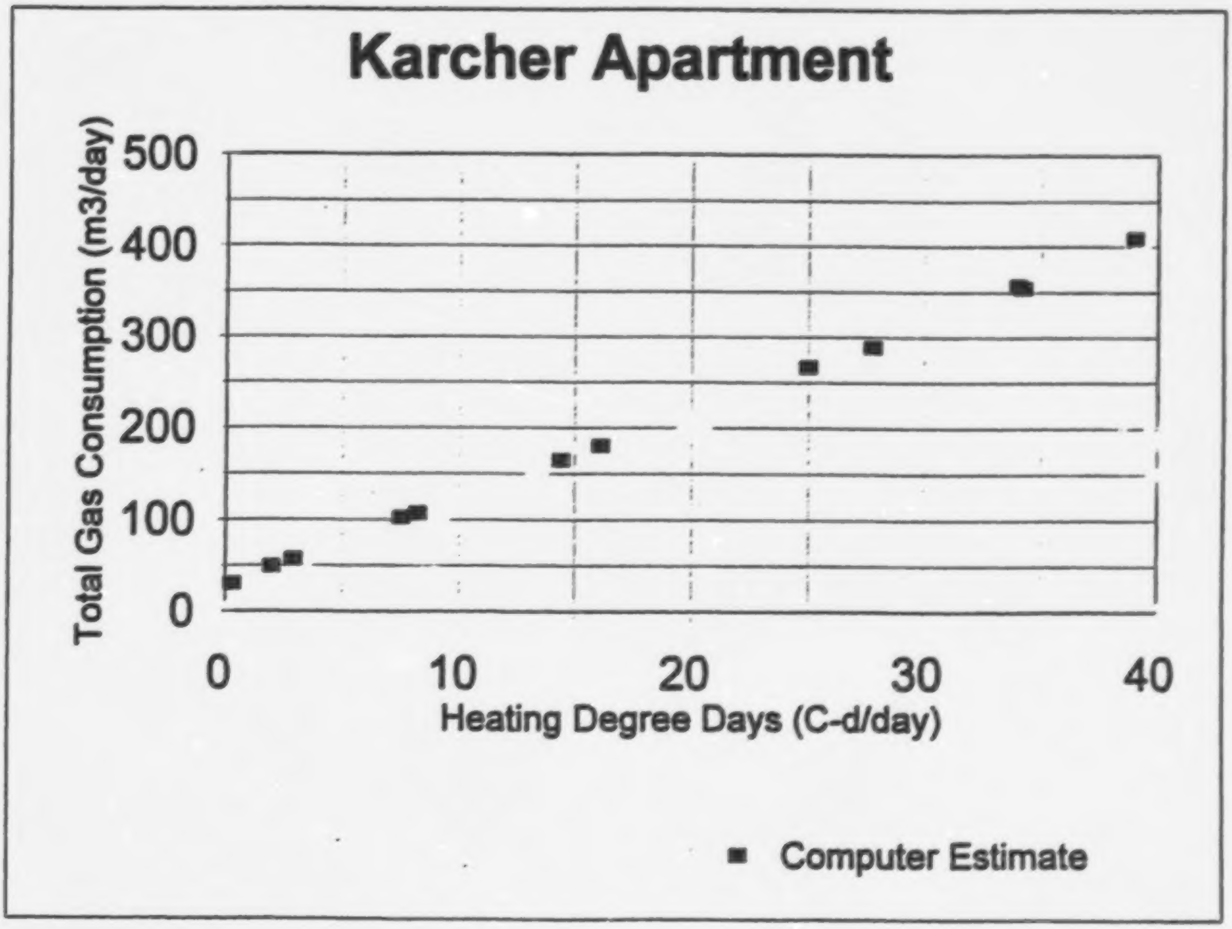
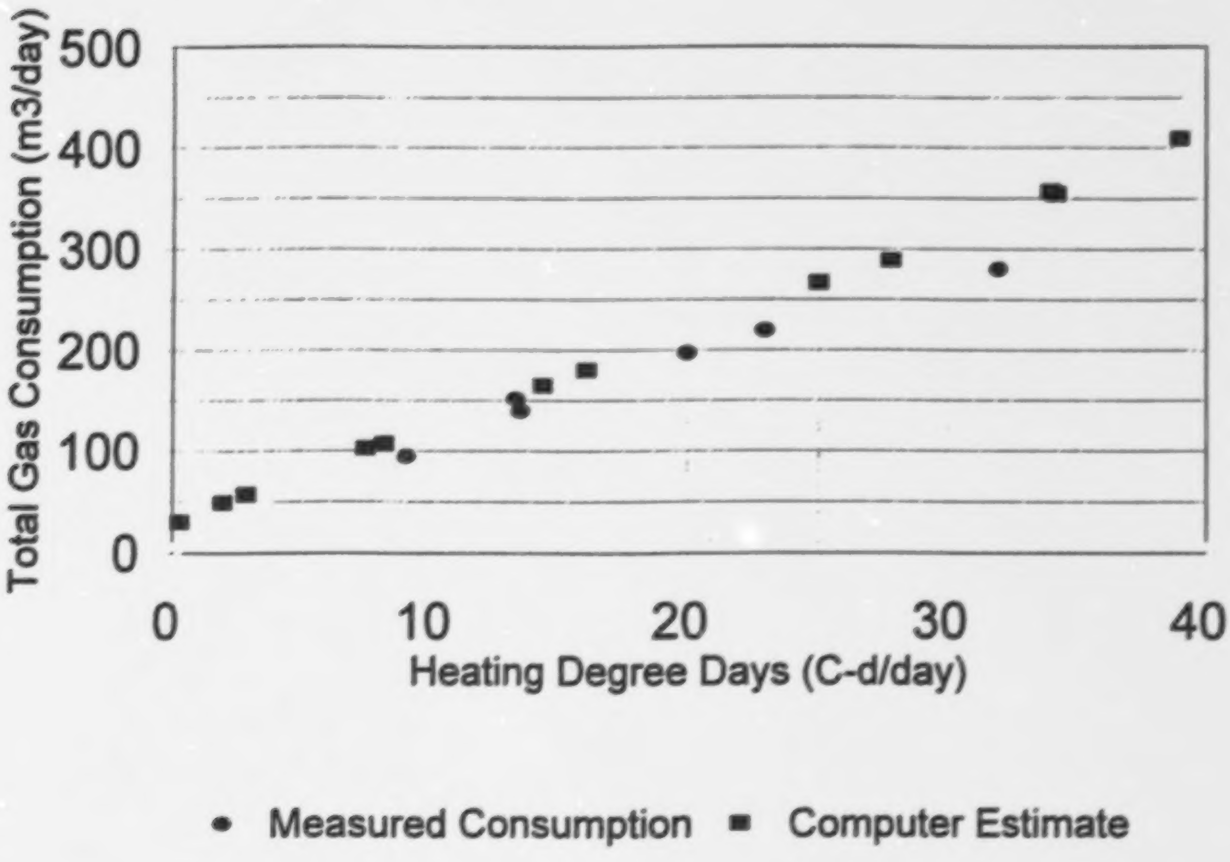


Figure 15. Comparison of HOT2000 Calculation with Measured Natural Gas Consumption for Karcher Building (Measured values from Dec. 97 to March 98)



INDOOR AIR QUALITY TESTING AT KARCHER APARTMENTS, PRINCE ALBERT, SK

J.T. Makohon, April 1998
Building Performance Section
Saskatchewan Research Council

1. BACKGROUND

Indoor air quality testing was performed at the Karcher Apartments over the time period of Feb. 11 to Feb. 25, 1998. Outdoor air temperatures ranged from a high of +5.7 °C to a low of -13.0 °C during that period. The daily means ranged from -0.1 to -11.0 °C.

2. SCOPE

Three suites were tested for carbon dioxide (CO_2), temperature (T), relative humidity (RH), formaldehyde, volatile organic compounds (VOCs), and particulates. In addition, tracer gas tests using nitrous oxide as the tracer gas were done to measure the ventilation rate for each suite.

Before testing was initiated, air flows were measured in each suite to establish that exhaust air flow balancing of the suites was correct. Suite 203 had no air flow as the ducting had become disconnected at the splitter box. This was fixed before the indoor air quality testing was started.

3 METHODOLOGY

The equipment/monitors used in the testing are listed in the following table.

Parameter	Monitor Brand Name/Description
Formaldehyde	Air Quality Research Institute (AQRI) PF1 passive samplers
Particulates	Particulate samplers - small calibrated sampling pump with 25 mm mixed cellulose ester filters
VOCs	SKC (575 Series) passive samplers
CO_2, T, RH	YES - 203 (scan rate set at 4 minutes)
Ventilation rate	Miran 1B2 multi-gas analyser and nitrous oxide gas

4 RESULTS

The three suites that were available for testing were Suite 113 (lower level), Suite 201, and Suite 203 (second level).

Formaldehyde was measured in two locations in each suite for the first week of testing. Particulates were measured twice - two 7 day periods in the same suite location while the VOCs were measured over the entire two week period. The T, RH, and CO_2 were recorded for the two week period. The ventilation rate was measured using the tracer gas for the whole suite on Feb. 11, 1998.

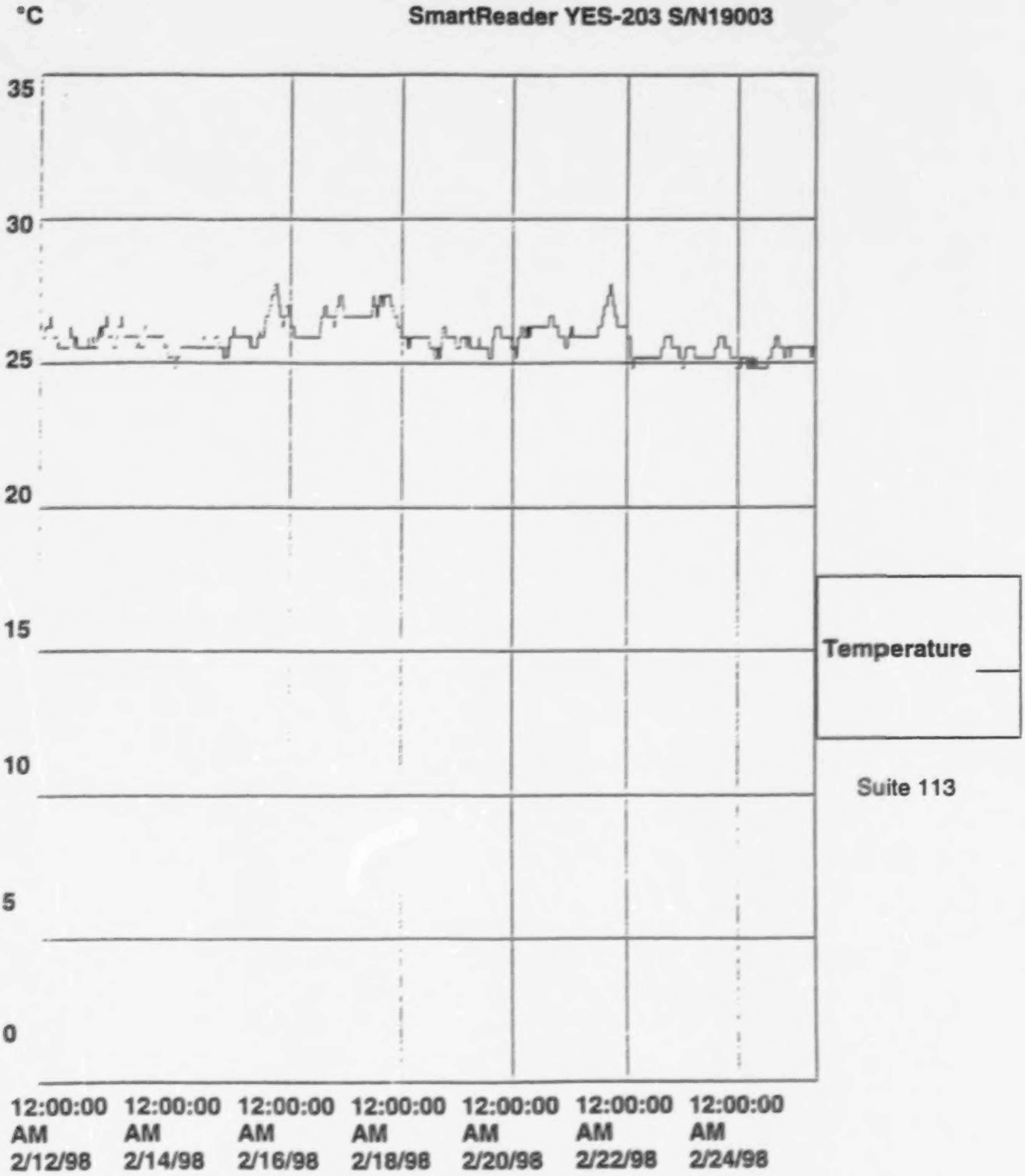
Parameter	Suite	Location	Concentration	Residential Guidelines (Canadian unless stated otherwise)
Formaldehyde	113	Kitchen	<0.01 ppm	0.05 target level 0.10 action level
	113	Bedroom	<0.01 ppm	
	201	Living room	<0.01 ppm	
	201	Bedroom	<0.01 ppm	
	203	Kitchen	<0.01 ppm	
	203	Living room	<0.01 ppm	
Particulates	113	Living room/kitchen	22 $\mu g/m^3$	40 µg/m3 ALTER
	113	Living room/kitchen	21 $\mu g/m^3$	
	201	Kitchen	5 $\mu g/m^3$	
	201	Kitchen	12 $\mu g/m^3$	
	203	Living room	23 $\mu g/m^3$	
	203	Living room	15 $\mu g/m^3$	
Volatile organic compounds	113	Kitchen	0.315 mg/m^3	1.0 mg/m^3 ASHRAE
	201	Living room	0.217 mg/m^3	

	203	Kitchen	0.380 mg/m^3	
Ventilation	113	Entire suite	0.97 ach	
	201	Entire suite	0.98 ach	
	203	Entire suite	0.56 ach	
Carbon dioxide (ppm)	113	Living room/kitchen	465 mean 380 low 836 high	3500 ppm ALTER
	201	Living room	421 mean 299 low* 630 high	
	203	Living room	569 mean 389 low 1114 high	
Temperature (degrees C)	113	Living room/kitchen	25.9 mean 24.8 low 27.7 high	
	201	Living room	27.4 mean 20.6 low 32.1 high	
	203	Living room	24.4 mean 21.6 low 26.6 high	
Relative humidity (%)	113	Living room/kitchen	5.6 mean 4.8 low 15.8 high	
	201	Living room	5.2 mean 3.2 low 16.8 high	
	203	Living room	9.8 mean 5.3 low 15.9 high	

* monitor accuracy +/- 100 ppm

ALTER = acceptable long-term exposure range

G:\BPDOCS\P-32\IAQ.WPD



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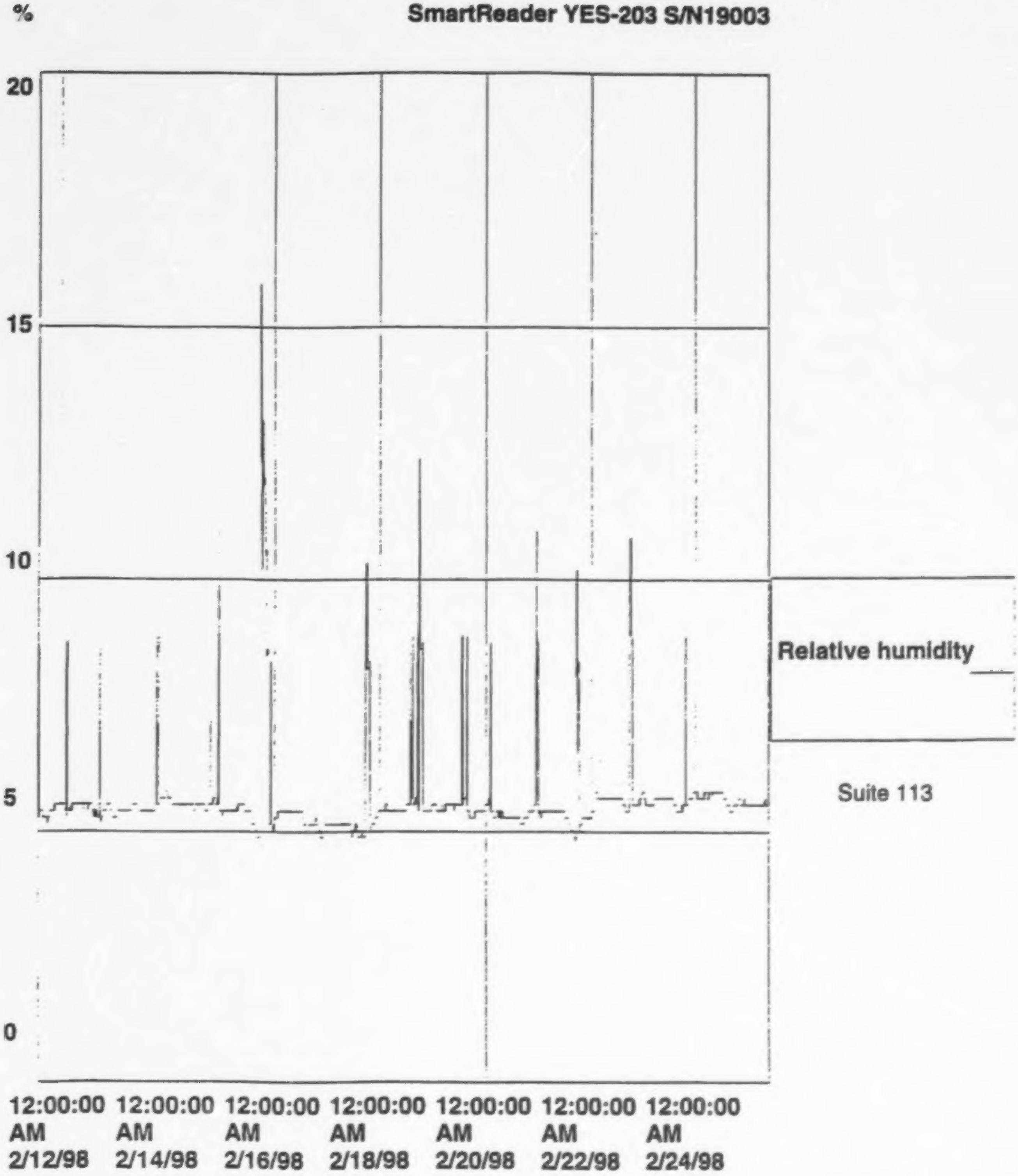
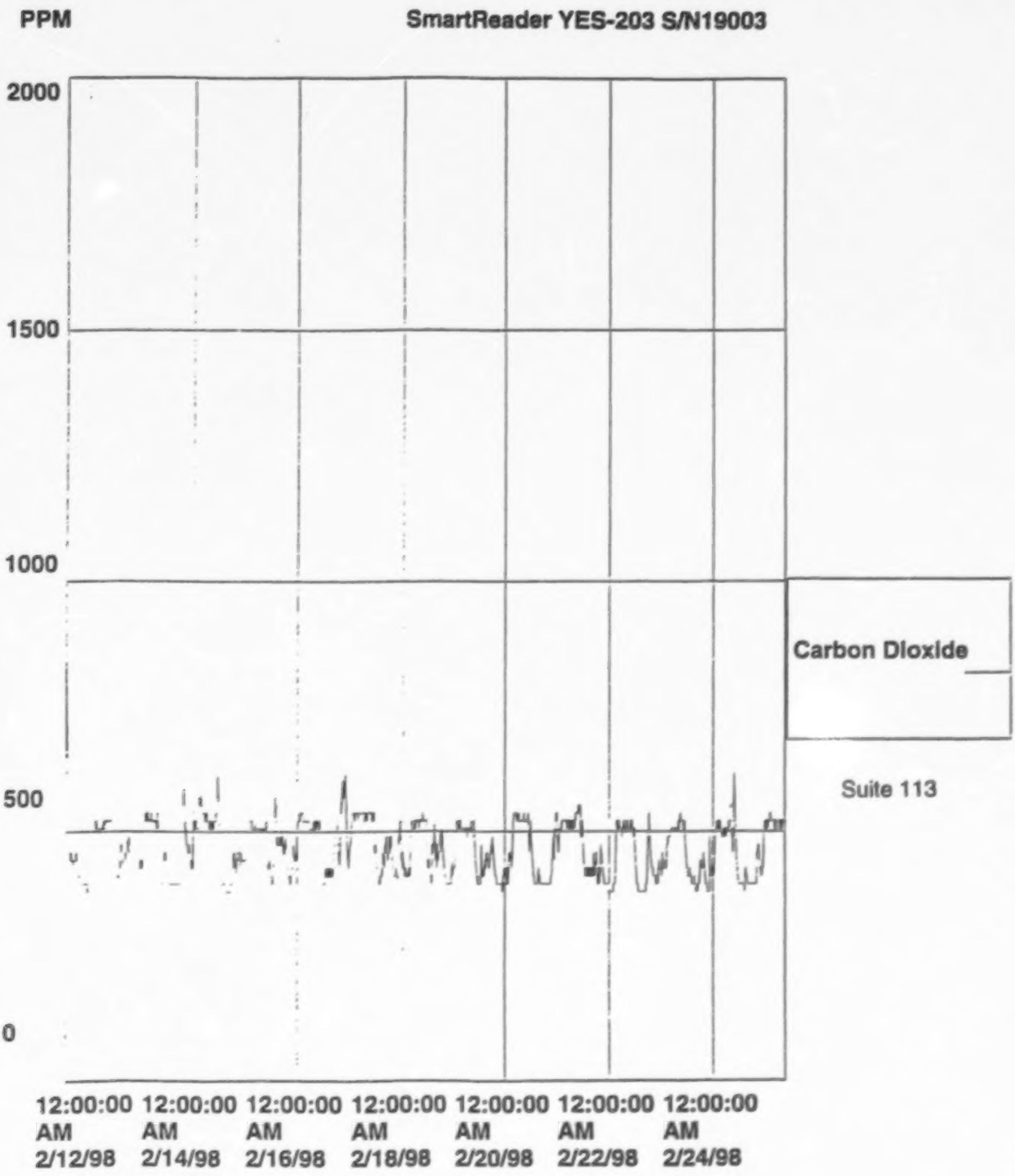

%
SmartReader YES-203 S/N19003
20
15
10
5
0
Relative humidity
Suite 113
12:00:00 AM 2/12/98
12:00:00 AM 2/14/98
12:00:00 AM 2/16/98
12:00:00 AM 2/18/98
12:00:00 AM 2/20/98
12:00:00 AM 2/22/98
12:00:00 AM 2/24/98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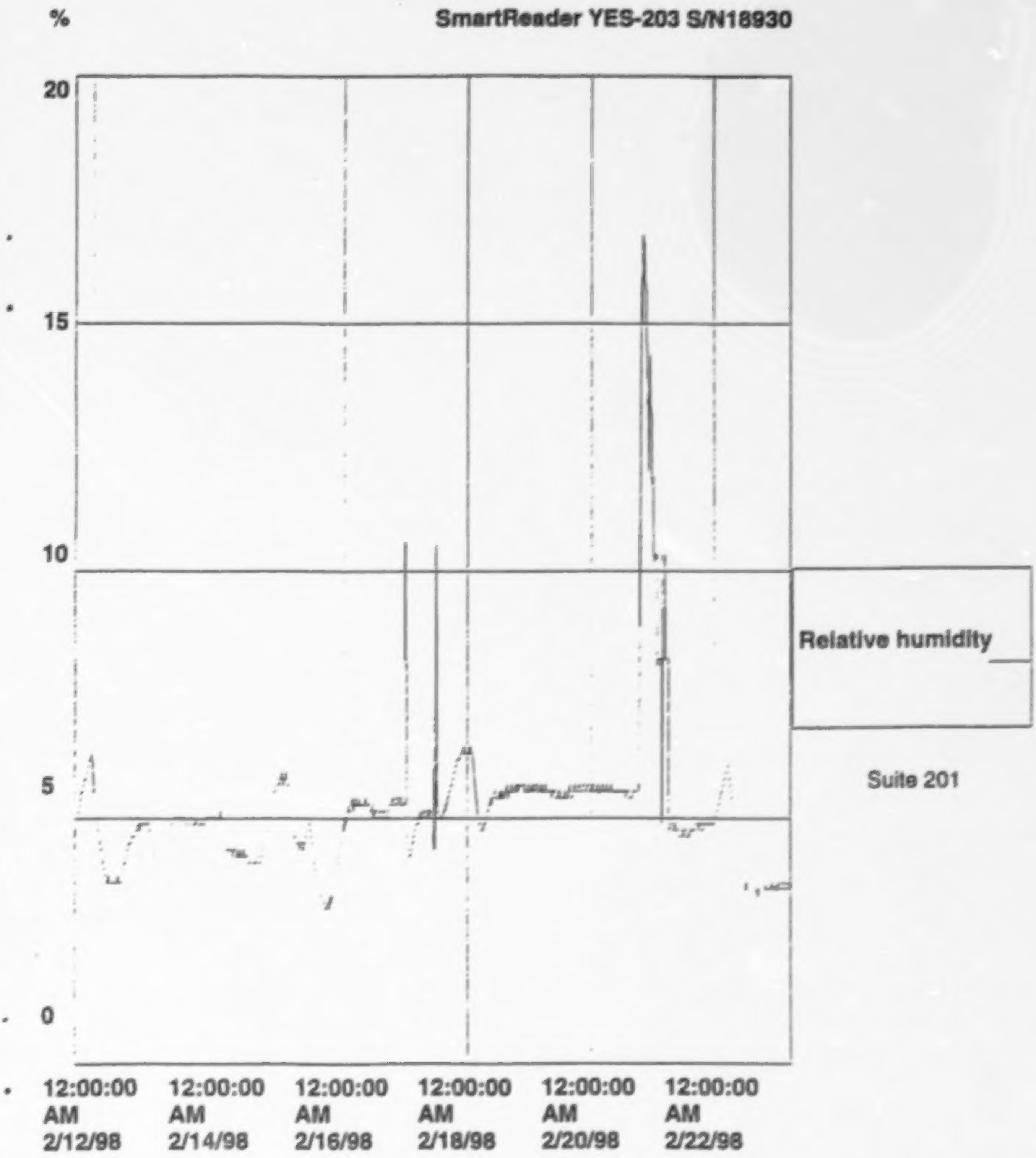
%
SmartReader YES-203 S/N18930
20
15
10
5
0
12:00:00 AM 2/12/98
12:00:00 AM 2/14/98
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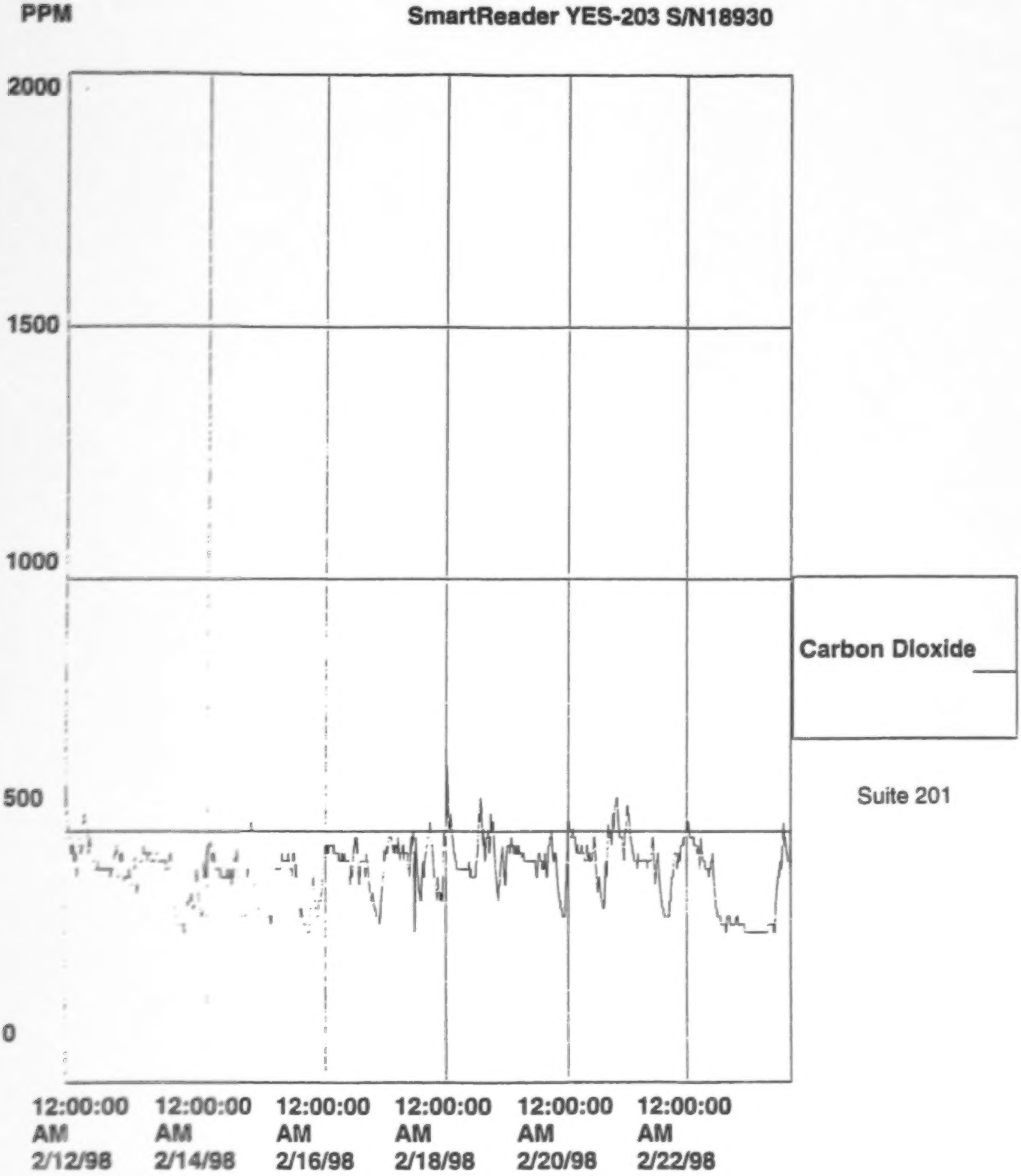
Relative humidity
Suite 201



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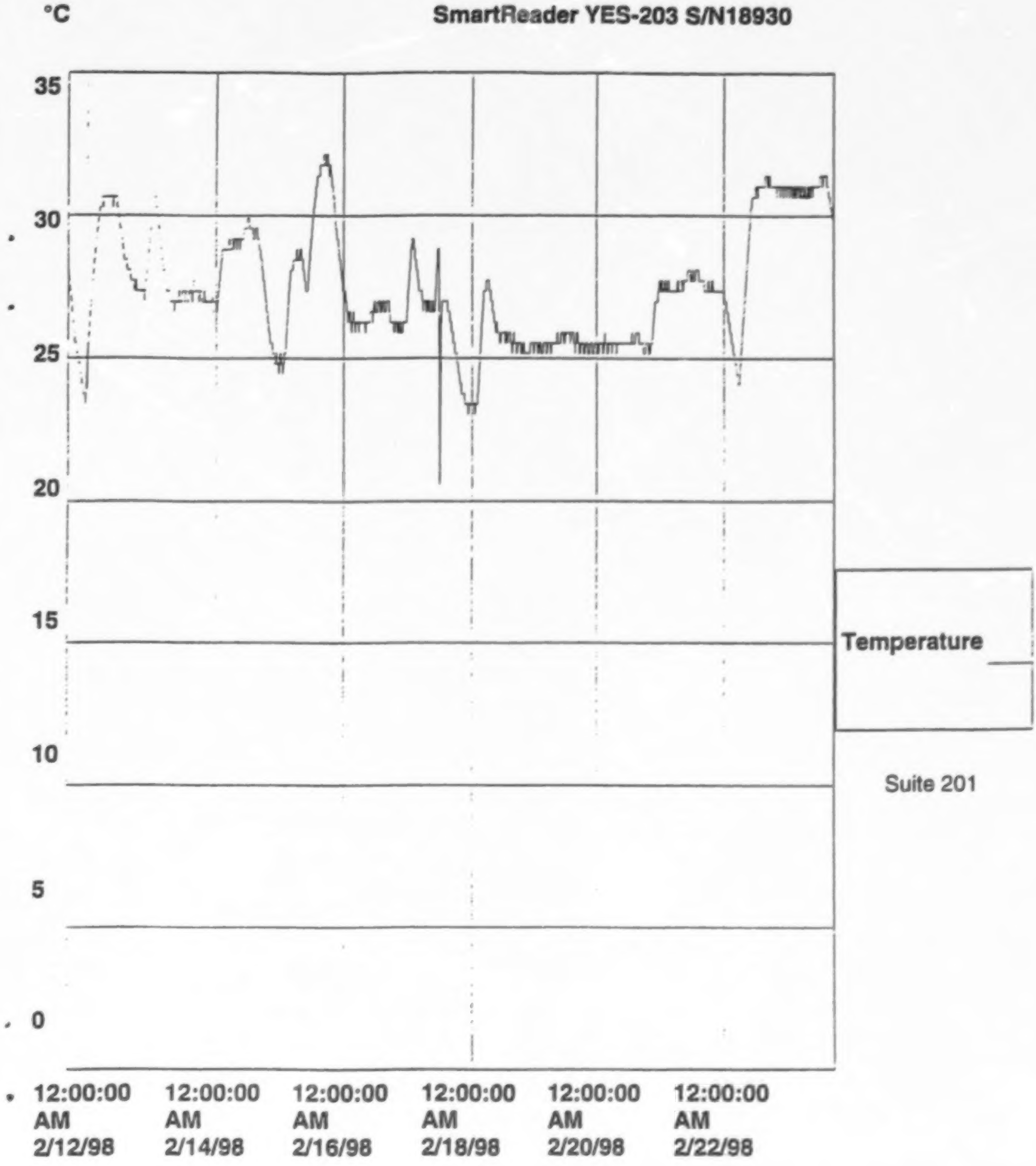
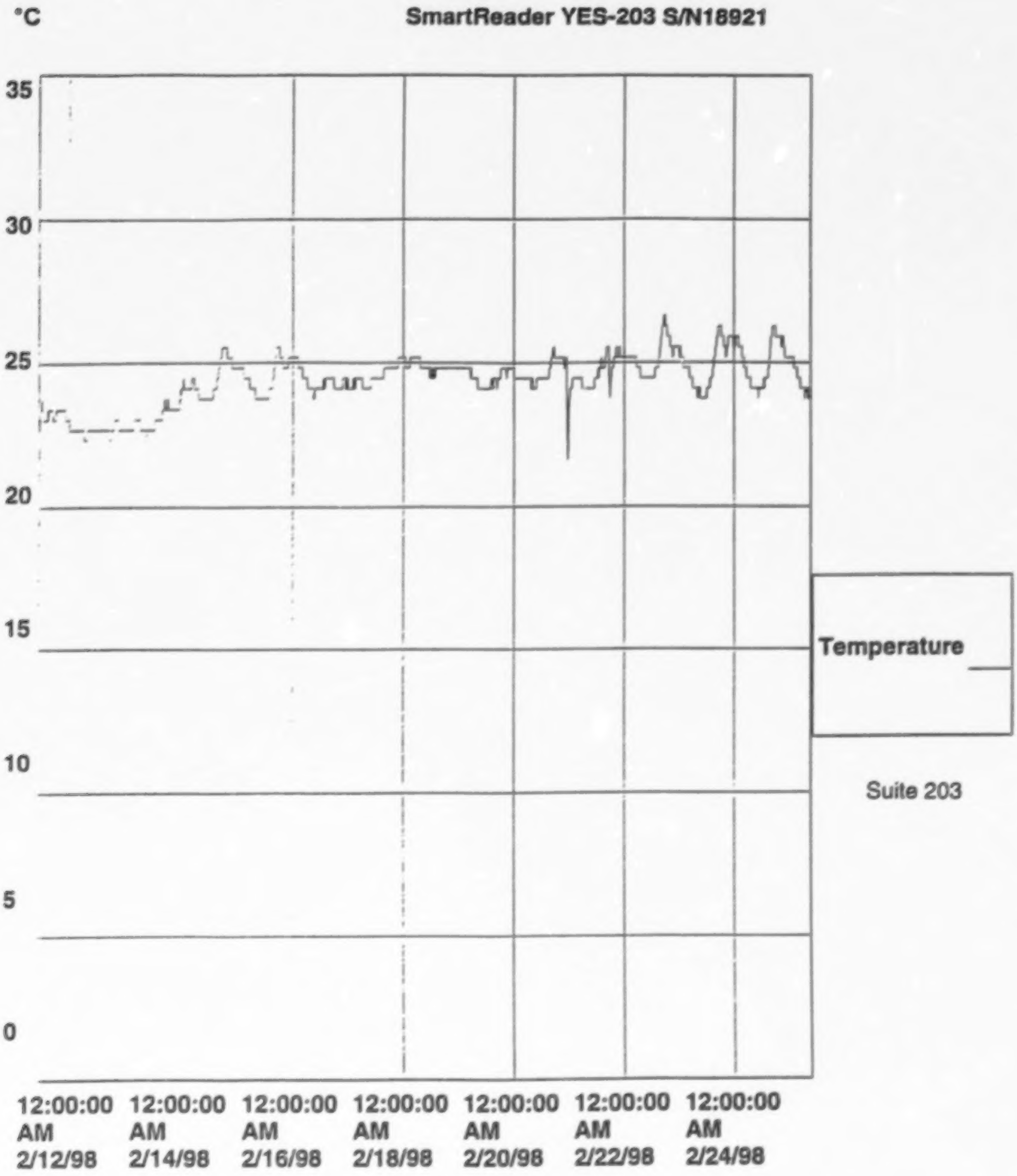
Suite 201

SmartReader YES-203 S/N18930




°C
SmartReader YES-203 S/N18921
35
30
25
20
15
10
5
0
12:00:00 AM 2/12/98
12:00:00 AM 2/14/98
12:00:00 AM 2/16/98
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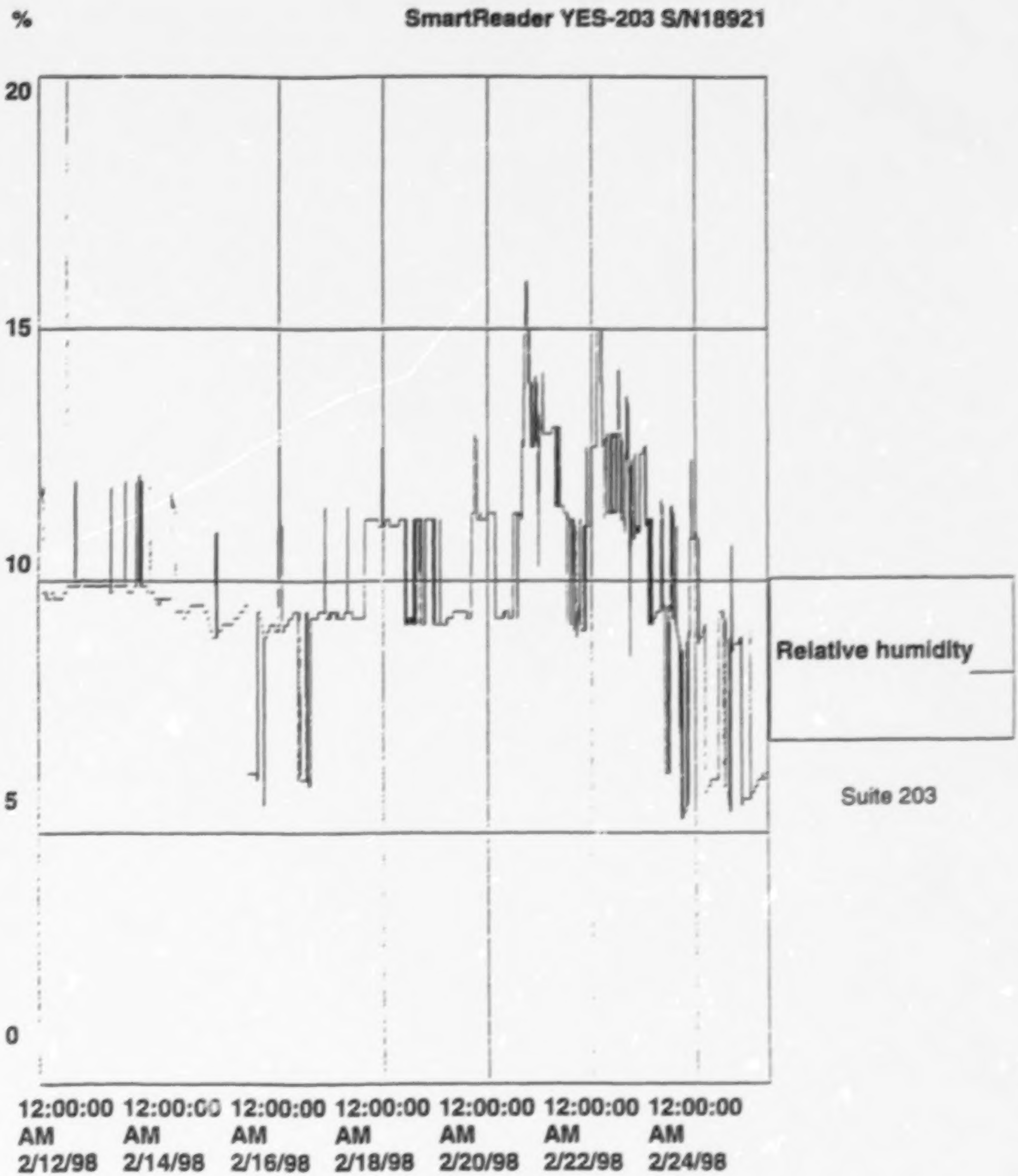
12:00:00 AM 2/24/98
Temperature
Suite 203


%
SmartReader YES-203 S/N18921
20
15
10
5
0
12:00:00 AM 2/12/98
12:00:00 AM 2/14/98
12:00:00 AM 2/16/98
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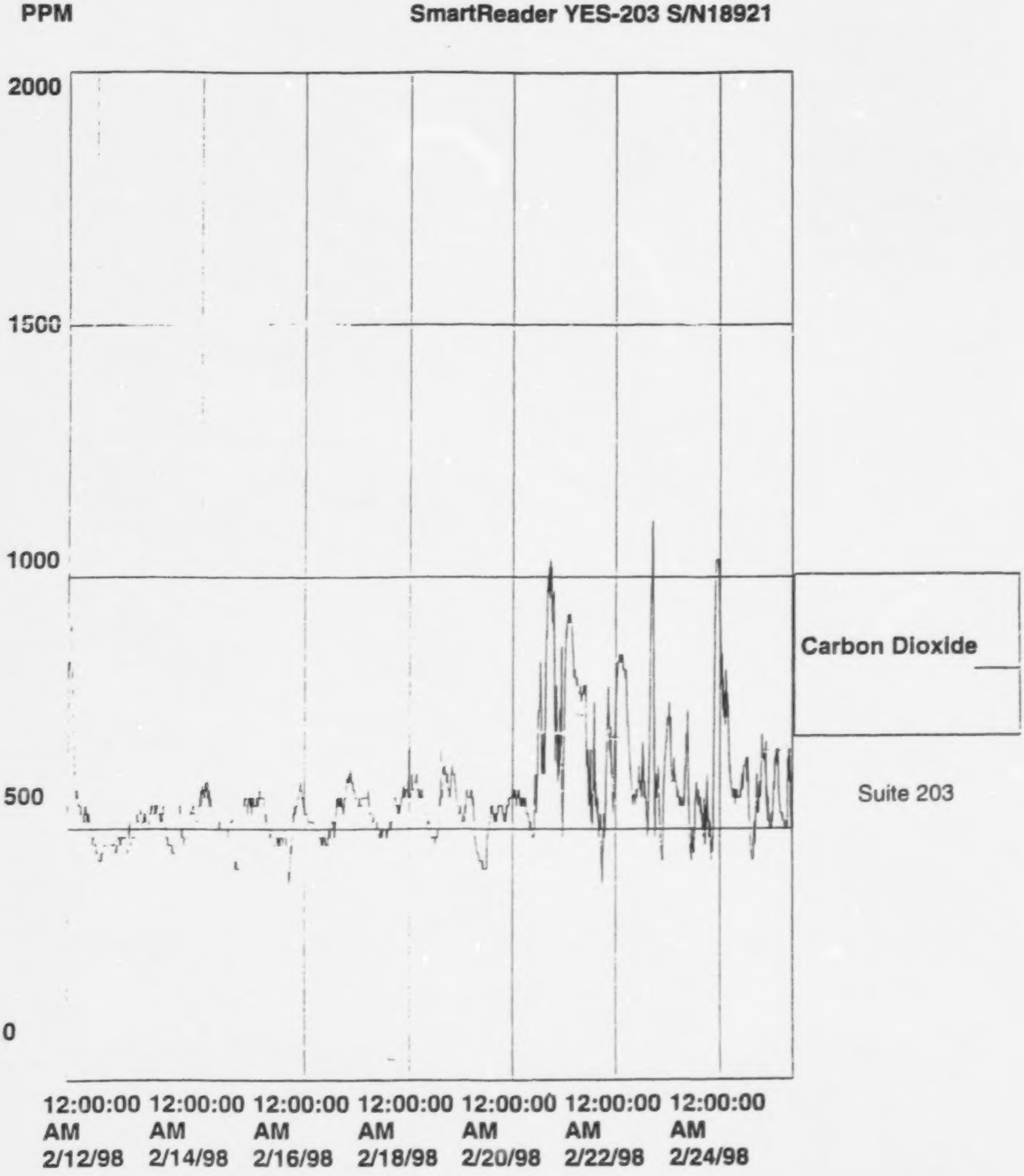
12:00:00 AM 2/24/98
Relative humidity
Suite 203


PPM
SmartReader YES-203 S/N18921
2000
1500
1000
500
0
Carbon Dioxide
Suite 203
12:00:00 AM 2/12/98
12:00:00 AM 2/14/98
12:00:00 AM 2/16/98
12:00:00 AM 2/18/98
12:00:00 AM 2/20/98
12:00:00 AM 2/22/98
12:00:00 AM 2/24/98